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STUDIES ON THE ACTION OF SULPHATES ON PORTLAND CEMENT

III. THE EFFECT OF THE ADDITION OF SILICA GEL TO PORTLAND CEMENT MORTARS ON THEIR RESISTANCE TO SULPHATE ACTION[1]

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Abstract

The effect of substituting silica gel for a portion of the Portland cement in standard and graded-sand mortars on the expansion and loss in strength of the mortars in sulphate solutions was determined. Portland cement silica gel sand mortars were cured in steam at 100° C. and the effect on their sulphate resistance measured; the behavior of lime-silica gel sand mortar in solutions of sodium and magnesium sulphate was also studied. It was found that the addition of silica gel to the mortar, very effective in preventing expansion and maintaining the tensile strength of the mortar in solutions of sodium, and calcium sulphate, was not so effective in solutions of magnesium sulphate. Steam-cured mortars containing silica gel to the extent of 20% of the cement present showed a slightly greater resistance to the action of solutions of sodium and calcium sulphates, but less resistance in solutions of magnesium sulphate, than similar steam-cured mortars containing no silica gel. Lime-silica gel sand mortars behaved very similarly in sulphate solutions as Portland cement mortars containing silica gel. The possible causes of the effects produced by the addition of silica gel to Portland cement mortars are considered, and several explanations discussed.

Introduction

The use as admixtures of finely divided highly siliceous materials, such as volcanic ash and diatomaceous earth, is fairly common for the purpose of decreasing the permeability of concrete and increasing its resistance to the action of sea water. The result obtained has been considered by some to be entirely due to a mechanically produced decrease in permeability, by others to be also partly due to a reaction between the free lime in the concrete and the added siliceous material. If the second explanation be correct it should

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be possible to estimate the value of a material for this purpose by determining its power of combining with hydrated lime; this can be done by methods similar to those used for determining the adsorption of a dissolved substance. The materials commonly used possess, to a greater or less degree, the property of adsorbing calcium hydroxide from an aqueous solution.

Silica in the form known as silica gel has an extremely high capacity for adsorbing calcium hydroxide from an aqueous solution. In some preliminary experiments carried out in this laboratory (3), it was found that silica in this form, when used as an admixture in Portland cement mortars, decreases very materially the rate of expansion of the mortars in dilute solutions of sodium and magnesium sulphate. This paper reports further experiments on the effect of admixtures of silica gel on the resistance of mortars to the action of sulphate solutions.

Description of Materials

Portland Cements. The physical tests[1] performed on the cements used are reported in Tables I and II and the chemical analyses in Table III.

TABLE I

PHYSICAL TESTS ON CEMENTS

Sample No.	Through sieve 200 mesh per in. per cent	Normal consistency per cent	Soundness in steam	Time of setting	
				Initial	Final
426	80	23.5	O.K.	4 hr	6 hr
127	91	25	O.K.	2 hr	4 hr
428	83	24	O.K.	2 hr 10 min.	4 hr

TABLE II

TENSION AND COMPRESSION TESTS*

Cement No.	Tension tests		Compression tests	
	7-day	28-day	7-day	28-day
426	235	330	1530	2540
127	375	435	3085	3785
428	315	–	–	–

**The tension was determined on 1:3 standard-sand briquets and the compression on 1:3 standard-sand cylinders (2 in. × 4 in.); both are given in pounds per sq. in.*

[1] *The authors are indebted to Professor G. M. Williams of the Department of Civil Engineering of the University of Saskatchewan for the physical tests given in Tables I and II.*

TABLE III

CHEMICAL ANALYSIS OF CEMENTS

Cement No.	SiO_2 per cent	Al_2O_3 per cent	Fe_2O_3 per cent	CaO per cent	MgO per cent	SO_3 per cent	Loss on ignition per cent
426	21.10	7.50	2.87	62.22	3.49	1.70	1.20
127	19.26	7.00	2.87	62.61	4.00	2.73	1.55
428	23.95	5.58	2.16	63.42	2.04	1.59	0.71

Silica Gel. The sample of silica gel used in the preliminary experiments was prepared in the laboratory from sodium silicate (water glass). The silica was recovered and purified by a method similar to that used in determining silica in soluble silicates. Several samples, the water content of which varied somewhat, were thus prepared. The non-volatile residue with hydrofluoric acid was about 0.2%. The sample used in the later experiments, known as "superpulverized silica gel", was obtained from The Silica Gel Corporation. It contained 11% water and after treatment with hydrofluoric acid, left a non-volatile residue of 0.3 %.

Experimental Methods

The two chief factors which influence the permanency of mortar and concrete when exposed to sulphate waters are the expansion, or tendency to expand, and the loss in tensile and compressive strength of the material. The changes in tensile or compressive strength can be determined only by destroying the specimens used in making each test, while specimens used for determining the expansion remain intact, if carefully handled, throughout the duration of the experiment. For this reason the effect of the sulphates on the mortar was in the main followed by exact measurements of the changes in length of the specimens used. With normal cement mortars it has been found that the loss in tensile strength can be predicted approximately from the linear expansion of the specimens (7, 11). However, it is not certain that modification of Portland cement, which influences the course of the chemical reactions taking place during the setting and hardening of the mortar or concrete made from it, will influence the tendency to expand and the rate of loss of strength in the same way; hence, a few determinations of tensile strength were also made, the same specimens being used for determining the expansion and the tension.

The methods used in preparing the mortar specimens and in determining their rate of expansion and tensile strength have been described in detail elsewhere (11). Unless otherwise stated the specimens used both for the expansion measurements and tensile strength tests were standard-sand mortar bars (0.625 in. $\times$ 0.625 in. $\times$ 7.5 in.). Silica gel when included in the mix displaced, unless otherwise stated, an equal weight of cement. Thus a 1:10 mix with 20% silica gel consisted of 0.8 parts Portland cement, 0.2 parts silica gel and 10 parts Ottawa sand. The cement and silica gel were always mixed thoroughly in a rotary shaker before being added to the sand. The bars were exposed to the solutions in air-tight glass jars to prevent evaporation.

TABLE IV

COMPARISON OF THE RATE OF EXPANSION OF STANDARD-SAND MORTAR BARS CONTAINING VARIOUS PROPORTIONS OF SILICA GEL*

Linear expansion per cent	0% silica gel	1% silica gel	2% silica gel	4% silica gel	7% silica gel	10% silica gel	15% silica gel	20% silica gel
A. in 0.15 M.Na_2SO_4								
0.02	4 days	4 days	4 days	4 days	4 days	3 days	3 days	4 days
0.05	6 days	7 days	7 days	8 days	17 days	25 days	35 days	3 years
0.10	9 days	10 days	11 days	13 days	96 days	10 months	0.08% in 3 years	
0.20	11 days	13 days	14 days	20 days	4.5 months	14 months		
0.50	14 days	17 days	19 days	28 days	5.5 months	16.5 months		
1.00	16 days	20 days	23 days	32 days	6 months	18 months		
B. In 0.50 M. Na_2SO_4								
0.02	3 days	3 days	3 days	4 days	3 days	3 days	3 days	3 days
0.05	5 days	6 days	6 days	6 days	6 days	8 days	21 days	17 months
0.10	9 days	10 days	10 days	12 days	20 days	3.5 months	0.08% in 3 years	0.05% in 3 years
0.20	12 days	13 days	13 days	18 days	34 days	5 months		
0.50	15 days	17 days	19 days	25 days	46 days	7 months		
1.00	19 days	22 days	26 days	30 days	53 days	8.3 months		
C. In 0.15 M.$MgSO_4$								
0.05	5 days	5 days	4 days	4 days	5 days	5 days	5 days	9 days
0.10	7 days	8 days	8 days	10 days	16 days	32 days	40 days	58 days
0.20	10 days	12 days	12 days	14 days	28 days	63 days	4 months	4 months
0.50	13 days	17 days	18 days	22 days	43 days	4 months	10 months	10 months
1.00	16 days	24 days	26 days	30 days	62 days	9 months	31 months	24 months
D. In 0.50 M. $MgSO_4$								
0.05	4 days	4 days	4 days	3 days	3 days	4 months	5 months	3 months
0.10	5 days	5 days	5 days	5 days	6 days	13 months	13 months	14 months
0.20	7 days	7 days	7 days	7 days	10 days	21 months	19 months	23 months
0.50	10 days	10 days	11 days	11 days	16 days	38 months	25 months	29 months
1.00	13 days	14 days	14 days	15 days	22 days	54 months	32 months	35 months

**Cement No. 426 plus silica gel; mix 1:5 (11.7% water); bars exposed to the solutions after curing 7 days in a damp closet*

The Effect on Sulphate Resistance of 1:5 Portland Cement Mortars Produced by the Displacement of a Portion of the Cement by Silica Gel

The relative expansion of 1:5 mortar bars, made from standard-sand and cement No. 426 with the substitution of from 1 to 20% of the cement by superpulverized silica gel, when exposed to solutions of sodium and magnesium sulphate, is given in Table IV. When calculating the mix no allowance was made for the 11% of water contained in the silica gel. The temperature of the room in which the specimens were exposed to the sulphate solutions was kept constant at 21°C. Three bars 0.625 in. × 0.625 in. × 7.5 in. were exposed to 1700 cc. of the solution.

At the end of three years exposure to the solutions the tensile strength of the bars described in Table IV, which were still intact, was determined. The results are given in Table V.

TABLE V

TENSILE STRENGTH OF 1:5 MORTARS CONTAINING SILICA GEL

Silica gel per cent	Tension in lb. per sq. in.				
	At time of exposure to solutions (7 days old)	After six months in damp closet	After three years exposure to:		
			$0.15M.Na_2SO_4$	$0.50M.Na_2SO_4$	$0.15M.MgSO_4$
10	130	260	–	–	125[a]
15	138	265	330	265	165[b]
20	–	–	365	405	100[c]

(*a*) *Linear expansion 2.4%;* (*b*) *linear expansion 1.2%;* (*c*) *linear expansion 1.3%*

The expansion measurements recorded in Table IV show that the addition of silica gel to the mortar retarded its expansion in sulphate solutions. The effect was noticeable with a quantity of 1% of silica gel and increased when this quantity was increased. It was much more marked for the bars exposed to solutions of sodium sulphate than for those exposed to solutions of magnesium sulphate. In the case studied, it was, however, necessary to substitute 15% or more of the weight of the cement in order to produce a mortar which approaches stability in solutions of sodium sulphate. The tensile strength determinations at the end of three years exposure to 0.15M. and 0.50M. solutions of sodium sulphate (Table V) confirmed the conclusion that such mortar is only slightly affected by solutions of this salt. The mortar bars made from the cement containing 15 and 20% of silica gel appeared in perfect condition at the end of three years exposure to the solutions of sodium sulphate.

Admixture of silica gel to the extent of 10 to 15% increased the resistance to solutions of magnesium sulphate. Addition of 20% did not appear to be of further value but rather increased the rate of expansion in concentrated solutions. None of the specimens was entirely stable in solutions of magnesium sulphate, although those containing the larger amounts of silica gel still possessed considerable strength at the end of three years exposure to 0.15M. magnesium sulphate; on the other hand, the bars containing no silica gel lost 90% of their strength after about two weeks exposure to the solution.

The results from another series of experiments in which the specimens were cured for 28 days in the damp closet before being exposed to the sulphate solutions were similar. The expansion at the early stages for quantities of silica gel up to 10% was retarded to a somewhat greater extent, but later was more rapid. In the case of the larger amounts of silica gel, the retardation held throughout.

Some of the mortars used by Larmour (3) were available for tension tests after they had been exposed to sulphate solutions for four years. The mortar bars were made from 0.87 part Portland cement, 0.13 part silica gel and 7.5 parts standard sand. The quantity of mixing water was 11.0% and the bars were cured for 28 days in the damp closet before being exposed to the sulphate solutions. The tensions of the bars after more than four years exposure to the solutions were as given in Table VI.

TABLE VI

TENSILE STRENGTH OF MORTAR BARS

Tension in lb. per sq. in.				
After 50 months exposure to:				
Distilled Water	10% Na_2SO_4	1% Na_2SO_4	1% $MgSO_4$	2% $MgSO_4$
230	200	215	215	125

Experiments with 1:10 Portland Cement Mortars Containing Silica Gel

In order to attempt to determine whether the effect of the addition of silica gel is mainly due to decreased permeability of the mortar to the solutions or to chemical stabilization of the cement, further experiments were carried out with a 1:10 standard-sand mortar. Silica gel was substituted for 20% of the cement so that the mortar was really only a 1:13 cement mortar. Concentrations of sulphate up to saturation were used. The expansion measurements for this series are given in Table VII and the tension of the more resistant specimens after 28 months exposure to the solutions in Table VIII.

TABLE VII

COMPARISON OF THE RATE OF EXPANSION IN SULPHATE SOLUTIONS AT 21° C. OF PLAIN 1:10 MORTAR, AND 1:10 MORTAR IN WHICH 20% OF THE CEMENT IS SUBSTITUTED BY SILICA GEL*

Linear expansion per cent	Concentration of Na_2SO_4 solution					Concentration of $MgSO_4$ solution					Concentration of $CaSO_4$ solution
	0.05M. 0.70%	0.15M. 2.09%	0.50M. 6.70%	1.00M. 12.7%	Saturated 17%	0.05M. 0.60%	0.15M. 1.77%	0.50M. 5.70%	1.00M. 10.8%	Saturated 26%	Saturated 0.21%
A. 1:10 standard-sand bars containing no silica gel											
0.02	1 day	1 day	1 day	1 day	1 day	1 day	1 day	1 day	1 day		1 day
0.05	7 days	4 days	3 days	2 days	3 days	4 days	3 days	2 days	2 days		6 days
0.10	12 days	7 days	5 days	3 days	5 days	6 days	6 days	3 days	4 days	1 day	9 days
0.20	18 days	10 days	7 days	4 days	6 days	7 days	7 days	5 days	5 days	1.5 days	13 days
0.50	40 days	13 days	10 days	6 days	9 days	10 days	10 days	7 days	6 days	2 days	20 days
1.00	105 days	15 days	12 days	8 days	12 days	11 days	13 days	9 days	7 days	2.5 days	33 days
B. 1:10 standard-sand bars containing silica gel											
0.02	3 days	2 days	1 day	1 day	1 day	1 day	1 day	1 day			1 day
0.05	0.02% in 28 months	0.03% in 28 months	28 months	28 months	0.04% in 28 months	40 days	10 days	5 days	1 day		0.04% in 28 months
0.10						0.06% in 28 months	20 days	7 days	2 days	1 day	
0.20							31 days	9 days	3 days	1.5 days	
0.50							53 days	13 days	4 days	2 days	
1.00							107 days	20 days	10 days	3 days	

*Cement No. 426, mix 1:10 (10.3% water); cured one month in damp closet before exposure to solutions

NOTE: Both A and B bars expanded 0.20% in water in 28 months

TABLE VIII

TENSION OF 1:10 MORTAR BARS, DESCRIBED IN TABLE VII, AFTER 28 MONTHS EXPOSURE TO SOLUTIONS

Tension at end of 28 months, in lb. per sq. in.										
Distilled Water		Concentration of Na_2SO_4 solution					Concentration of $MgSO_4$ solution		Concentration of $CaSO_4$ solution
A	B	0.05M.	0.15M.	0.50M.	1.00M.	Saturated	0.05M.	0.15M.	Saturated
65*	210	260	240	210	195	235	135	46**	260

**No silica gel*
***Expansion 1.1%*

The results given in Tables VII and VIII show in a most striking manner the effect on the expansion and tensile strength of the substitution of silica gel for 20% of the cement in a Portland cement mortar when exposed to water, or to solutions of sodium sulphate and calcium sulphate. The marked difference in the behavior of such a very lean mortar on exposure to solutions of different sulphates leaves no doubt that the quantity of silica used has almost entirely stabilized the hydrated cement in the mortar towards the action of solutions of calcium and sodium sulphate of any concentration. The effect observed could not be due to a change in permeability produced by the silica gel, but to a modification of the products of hydration of the cement which prevents the action of the sulphate on these. While the expansion and loss in strength in dilute solutions of magnesium sulphate are retarded very markedly, the hydrated cement is not stabilized against the action of this salt.

Further Experiments with Standard and Graded-Sand Mortars

The Portland cement (No. 426) used in the experiments so far described was one which had a very low resistance to the action of sulphate solutions. Further systematic tests were therefore begun with mortars of varying richness of mix (from 1:10 to 1:3) prepared with Portland cement (No. 428) which had a considerably higher resistance to sulphate action. Both standard-sand and graded-sand mortars were used. At the end of five months exposure, the results obtained with the leaner mixes were similar to those given above. There was very little expansion in solutions of sodium sulphate in the case of the mortars containing silica gel to the extent of 20% of the cement, and no expansion for the corresponding 1:3 mortar. Addition of 10% silica gel did not stop the expansion of mortars. Gradual increase in richness of mix, however, progressively retarded the expansion which was extremely small for the 1:3 mortar. The 1:3 graded-sand mortar did not show any improvement over the 1:3 standard-sand mortar in solutions of sodium or calcium sulphate, but showed some improvement in solutions of magnesium sulphate.

TABLE IX

THE EXPANSION OF STEAM-CURED PORTLAND CEMENT SILICA GEL MORTARS IN SULPHATE SOLUTIONS AT 21° C.*

Linear expansion per cent	Time of steam-curing at 100° C.					
	None	5 days	None	5 days	None	5 days
	No silica gel	No silica gel	5% silica gel	5% silica gel	20% silica gel	20% silica gel
A. In 0.15 M.Na_2SO_4						
0.02	3 days	9 days	3 days	13 days	2 months	18 months
		0.04% in				
0.05	5 days	18 months	6 days	10 months	18 months	
				0.07% in		
0.10	6 days		8 days	18 months		
0.20	7 days		10 days			
0.50	9 days		12 days			
1.00	11 days		19 days			
B. In 0.50 M.Na_2SO_4						
0.02	3 days	9 days	3 days	15 days	12 days	1 month
						0.04% in
0.05	5 days	18 months	6 days	2 months	2 months	18 months
0.10	6 days		9 days	10 months	12 months	
					0.13% in	
0.20	9 days		14 days	20 months	18 months	
0.50	12 days		24 days			
1.00	17 days		45 days			
C. In 0.15 M.$MgSO_4$						
0.02	1 day	1 day	1 day	1 day	3 days	2 days
0.05	3 days	7 days	3 days	3 days	9 days	7 days
0.10	4 days	42 days	5 days	13 days	12 days	11 days
0.20	5 days	4 months	7 days	36 days	17 days	15 days
		0.3% in				
0.50	7 days	18 months	11 days	6 months	21 days	21 days
				0.67% in		
1.00	10 days		16 days	18 months	27 days	31 days
D. In saturated $CaSO_4$						
0.02	9 days	1 month	13 days	13 days	3 months	18 months
		0.03% in			0.03% in	
0.05	11 days	18 months	45 days	18 months	18 months	
0.10	13 days		2 months			
0.20	18 days		2.5 months			
0.50	27 days		3.5 months			
1.00	37 days		5 months			

**Cement No. 127; mix 1:10 (10.7% water); total time of curing 15 days*

Steam-curing of Portland Cement Mortars Containing Silica Gel Admixtures

The very great increase in resistance of Portland cement mortars to sulphate action produced by curing in steam at temperatures of 100° C. or above (10) suggested that steam-curing of mortars containing admixtures of silica gel may produce a resistance of a still higher order. Only preliminary experiments with steam at 100°C. have so far been completed. It was found that mortar bars of cement No. 127 containing 20% silica gel did not expand as much on curing five days in steam at 100° C. as bars containing no silica. The average linear expansions resulting from the steam-curing were:

For 1:10 Mortar bars....................... 0.033%
For 1:10 Mortar bars (5% silica gel)......... 0.033%
For 1:10 Mortar bars (20% silica gel)......... None

The results of 18 months exposure of the steam-cured bars, containing 5 and 20% silica gel substituted for an equivalent weight of cement, are given in Tables IX and X.

TABLE X

THE TENSILE STRENGTH OF STEAM-CURED PORTLAND CEMENT SILICA GEL MORTAR BARS*

Silica gel per cent	Duration of steam-curing at 100° C.	Tension in lb. per sq. in. after exposure for 18 months in:				
		0.15M.Na_2SO_4	0.50M.Na_2SO_4	0.15M.$MgSO_4$	Saturated $CaSO_4$	Distilled water
None	5 days	44	31	155	39	–
5	5 days	31	21	127	28	–
20	None	187	164	–	191	–
20	5 days	151	160	–	173	120

**After exposure to sulphate solutions for 18 months at 21° C.*

NOTE: Cement No. 127; mix 1:10 (10.7% water); total time of curing 15 days

From Tables IX and X it is seen that Portland cement mortars containing silica gel cured in steam at 100° C. do not possess any marked advantage over steam-cured plain Portland cement mortars as to their resistance to sulphate solutions. While the mortar with 5% silica, steam-cured at 100° C. for five days, expands somewhat faster than similarly treated plain mortar in solutions of sodium sulphate and calcium sulphate, the mortar with 20% silica is improved by steam-curing, and is superior to both the bars containing 20% silica but not steam-cured and the plain steam-cured bars. The improvement as to expansion, however, appears to be counterbalanced by a slight decrease of tensile strength produced after an exposure of 18 months. It is possible that

mortars in which the silica gel replaces not more than 10% of the cement would, if cured in steam under pressure, acquire a higher resistance to the action of magnesium sulphate solutions.

The Resistance of Lime-Silica Gel Mortars to Sulphate Action

The marked increase in the tensile strength of mortar specimens containing silica gel when exposed to water suggests that the products formed by the interaction of the free lime and silica gel may act as a cement. In order to study the action of sulphate solutions on the material resulting from the reaction between calcium hydroxide and silica gel independently of Portland cement, bars were prepared with mortar consisting of lime, silica gel and standard sand, and the expansion during exposure to sulphate solutions measured in the usual manner. The changes in the tensile strength of the more highly resistant specimens were also determined.

The lime used was prepared from a pure sample of ignited calcium oxide by hydrating with excess of water and drying to constant weight at 100°C. in a current of carbon dioxide-free air. This sample lost 25% of its weight on ignition, and had a calcium oxide content of 74.2%. The calcium hydroxide and the superpulverized silica gel were thoroughly mixed in molecular proportions in a ball mill, and then made into a mortar containing one part by weight of the lime-silica gel mixture (on the basis of anhydrous CaO and SiO_2) to five parts of standard sand. Water was added until a fairly plastic mix was obtained, the water used amounting to 17%. The time of set was not determined but the mortar had set hard when examined 18 hours after mixing. The mortar bars were removed from the moulds when seven days old, and were apparently as strong as the ordinary 1:5 Portland cement mortar bars at that age. They were stored in a dessiccator over water to prevent absorption of carbon dioxide until exposed to the sulphate solutions.

The free lime determined in the mortar by Emley's method (4) eight days after the specimens were prepared, was only 0.5% CaO. The solid material, however, remained pink although the solution was colorless. The free lime in the original lime-silica gel mixture after shaking in the ball mill was found by the same method to be 33% CaO as against 38% CaO actually put into the mixture. As absorption of more than a trace of carbon dioxide was out of the question it appeared that the lime had reacted with the silica so that its presence could not be detected by this method.

The results obtained on exposure of the specimens, prepared with lime, silica gel and standard-sand, to solutions of sodium and magnesium sulphate when eight days old are given in Table XI.

TABLE XI

Expansion in sulphate solution of mortar made with lime, silica gel and standard sand*

Linear expansion per cent	In distilled water	In 0.15M. Na_2SO_4	In 0.5M. Na_2SO_4	In 0.15M. $MgSO_4$
0.01	1 day	1 day	1 day	1 day
0.02	9 months	15 months	15 months	2 days
	0.03% in 2.5 years	0.03% in 2.5 years		
0.05			2 years	12 days
			0.06% in 2.5 years	
0.10				14 days
0.20				16 days
0.50				19 days
1.00				24 days
Tension after 2.5 years	420 lb. per sq. in.	310 lb. per sq. in.	150 lb. per sq. in.	—

**Mix 1 part lime silica gel mixture ($CaO:SiO_2$) to 5 parts standard sand. The bars were cured 8 days in damp closet before exposure to sulphate solutions. Tensile strength of briquets 28 days old, 235 lb. per sq. in.*

The product formed by the reaction between the hydrated lime and silica gel is apparently very stable in solutions of sodium sulphate while it is no more stable than hydrated Portland cement in solutions of magnesium sulphate. The behavior of this mortar in sulphate solutions is thus strikingly similar to a 1:5 Portland cement mortar in which 15% of the cement has been replaced by silica gel (Tables IV and V). This suggests a reason for the marked increase in resistance to the action of sodium sulphate of the 1:5 Portland cement mortar containing 15% silica gel used for the experiments recorded in Table IV. The reason is that this concentration of silica gel is sufficient to bind all the lime liberated by hydrolysis of the cement, with the formation of a product of high stability in solutions of sodium sulphate.

Possible Explanation of the Effect of Silica Gel on the Sulphate Resistance of Portland Cement Mortars

There is little doubt that the direct result of the presence of a sufficient quantity of silica gel in a Portland cement mortar is the combination with the active silica of the free lime liberated during hydrolysis of the silicates. The product formed is a gel which does not appear to crystallize readily; it must be fairly resistant to the action of sodium and calcium sulphate, judging by the behavior of Portland cement-silica gel mortar and lime-silica gel mortar in solutions of these sulphates.

The most striking effect of the presence of a sufficient quantity of silica gel in a Portland cement mortar is to render it very resistant to the action of solutions of sodium sulphate. It has been found (9) that mortars made of

pure tricalcium silicate and sand or pure dicalcium silicate and sand are extremely resistant to the action of solutions of sodium sulphate, and disintegrate very slowly in solutions of magnesium sulphate. Since a large quantity of free lime is liberated during the hydration of these two silicates the presence of free calcium hydroxide cannot be a direct cause of failure of a mortar, nor can the removal of this calcium hydroxide by silica be directly responsible for the increased stability in solutions of sodium sulphate.

The effect of proper steam-curing of Portland cement sand mortars (10) is to render them very stable in solutions of sodium and calcium sulphate and to increase appreciably their resistance to solutions of magnesium sulphate. In fact steam-cured mortars behave very similarly to mortars made from the pure silicates. It has been found (8) that during steam-curing the free lime, liberated by hydration of the cement, disappears with the formation of a crystalline product rich in lime and apparently containing silica. These crystals are fairly resistant to the action of magnesium sulphate, and as would be expected the resistance of steam-cured mortar to the action of solutions of magnesium sulphate is increased very materially.

Thus both the addition of silica gel and steam-curing seem to result in the removal of free lime; in the first case a gelatinous product is formed, and in the second case a crystalline product. In each case the effect on the resistance to solutions of sodium and calcium sulphate is very similar and the difference in the resistance produced towards solutions of magnesium sulphate might be one of degree, namely, the difference between the rate of action on a colloid gel in the one case and on crystalline particles in the other case.

The addition of tricalcium aluminate to mortars made from either pure tricalcium silicate or pure dicalcium silicate causes them to fail in solutions of sodium sulphate as well as in solutions of magnesium sulphate (9). This seems to present strong evidence that it is the tricalcium aluminate in Portland cement which renders the mortar vulnerable to the action of sodium sulphate and causes rapid disintegration in solutions of magnesium sulphate. Why then should the removal of free lime from Portland cement mortars during steam-curing and by reaction with silica gel cause the mortar to behave as if it contained no tricalcium aluminate?

It has been shown that during hydration in steam an isotropic crystalline variety of tricalcium aluminate is formed (5) instead of the hexagonal plates, needles and spherulites ordinarily formed when tricalcium aluminate is hydrated. This isotropic variety is fairly stable, is not easily hydrolyzed, and has a much lower solubility in water than the hexagonal form (6). These facts may account at least partly for the high stability of steam-treated Portland cement mortars in sulphate solutions.

An explanation of the effect of silica gel is suggested by the possibility that the tricalcium aluminate may be hydrolyzed in a mixture of the usual form of hydrated tricalcium aluminate and silica gel, the latter keeping the concentration of lime in the solution below that necessary to prevent continued

hydrolysis. In some experiments shaking tricalcium aluminate, silica gel and water together failed to prevent the formation and persistence of hexagonal plates of hydrated tricalcium aluminate. It seems therefore that even with a large excess of silica gel present the hydrated tricalcium aluminate is not completely hydrolyzed.

Desch (1) and later Kühl and Thüring (2) have reported the apparent formation of a tetracalcium aluminate in the presence of excess of calcium hydroxide. It is possible that the great reactivity of tricalcium aluminate in the presence of free calcium hydroxide is due to the formation of hydrated tetracalcium aluminate and the interaction of this product with the sulphates. This would explain why removal of free lime from the mortar stabilizes the mortar in solutions of sodium and calcium sulphate and causes the action in magnesium sulphate to be retarded until it is comparable to the action of these solutions on the pure silicates and pure hydrated tricalcium aluminate.

Experiments carried out in this laboratory have indicated that when tricalcium aluminate is hydrated in a saturated solution of calcium hydroxide a certain amount of peptization of hydrated tricalcium aluminate takes place. The greatly increased reactivity of this substance in the colloidal as compared with the crystalline state may explain the harmful effect of the presence of excess of lime on the resistance of a Portland cement mortar to sulphate action.

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A STUDY OF SOME FACTORS INFLUENCING THE ACTIVITY OF ALUMINUM AND FERRIC CHLORIDES IN THE FRIEDEL AND CRAFTS REACTION[1]

By M. C. Boswell[2] and R. R. McLaughlin[3]

Abstract

In the preparation of aluminum chloride by the action of hydrogen chloride on the metal, hydrogen chloride is adsorbed and can be recovered to the extent of about 9 cc. per gram. After sublimation in nitrogen and re-sublimation in hydrogen chloride, however, the amount of adsorption is smaller and irregular. The adsorbed gas is not removed by a stream of nitrogen at room temperature. The activities in the Friedel and Crafts reaction of various preparations of aluminum chloride and of ferric chloride and of mixtures of these were determined; the order of decreasing activity was found to be as follows: a mixture of aluminum chloride and ferric chloride, aluminum chloride made by the action of hydrogen chloride on aluminum, aluminum chloride made by the action of chlorine on aluminum, a mixture of aluminum chloride and partially reduced ferric chloride, ferric chloride, and partially reduced ferric chloride. The most striking result of the measurements is that although ferric chloride alone has an activity of only about one-third that of aluminum chloride, an approximately equimolecular mixture of the two has an activity somewhat greater than that of pure aluminum chloride.

Introduction

It is well known that aluminum oxide, which is remarkably stable towards hydrogen, even at high temperatures, has a large capacity for absorbing water. Dilworth (1), in this laboratory, has shown that the catalytic activity of aluminum oxide in dehydration actions, as well as its capacity for adsorption, depends upon its water content. Likewise, it was thought that since aluminum chloride is reduced with difficulty in hydrogen, its activity in the splitting off of hydrogen chloride in the Friedel and Crafts reaction might be influenced by the presence or absence of adsorbed hydrogen chloride. In fact, experiments described in this paper show that aluminum chloride, prepared by the action of hydrogen chloride on aluminum, contains adsorbed hydrogen chloride to an extent which may equal 9 cc. per gram; also that the presence of this adsorbed hydrogen chloride is apparently somewhat unfavorable to catalytic activity in the Friedel and Crafts reaction, since its removal by sublimation in nitrogen raises the activity. The amount of hydrogen chloride adsorbed during the preparation of aluminum chloride from the metal and hydrogen chloride is very considerably greater than that which aluminum chloride is capable of adsorbing by sublimation in the gas after first being freed from the hydrogen chloride taken up during preparation.

Quantitative comparisons of its catalytic activity in the Friedel and Crafts reaction showed that aluminum chloride made by the action of chlorine is somewhat less active than that made by the action of hydrogen chloride on

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the metal, and that ferric chloride, especially if partially reduced, is very much less active than aluminum chloride. The comparisons revealed, further, the striking fact that, although ferric chloride alone has an activity not much more than one-third that of aluminum chloride, an approximately equimolecular mixture of the two materials has a catalytic activity somewhat greater than pure aluminum chloride itself.

Experimental

Adsorption of hydrogen chloride by aluminum chloride

3.5 gm aluminum was converted into the chloride by heating in a current or dry hydrogen chloride. Free hydrogen chloride was swept out of the tube by a stream of dry nitrogen at room temperature. The aluminum chloride was then sublimed in a current of nitrogen from one part of the tube to another, the gases issuing from the tube being passed through standard alkali solution. Care was taken that no aluminum chloride escaped during sublimation. The sublimation was repeated until no further hydrogen chloride was evolved. Titration of the standard alkali solution indicated that the hydrogen chloride evolved in two experiments was: (1) 147 cc., (2) 98 cc., corresponding to 9 cc. and 6 cc., respectively, per gram of aluminum chloride.

In the first experiment, after removal of adsorbed hydrogen chloride in the way described, dry hydrogen chloride was passed over the material while it was sublimed back and forth several times; dry nitrogen was then passed at room temperature in order to displace free hydrogen chloride from the tube, and the adsorbed hydrogen chloride was determined as before by removal during sublimation. It was found that only 35.5 cc. hydrogen chloride had been adsorbed by the aluminum chloride, as compared with 147 cc. adsorbed during its preparation. That there was no source of error due to sublimation of aluminum chloride from the tube, was shown by acidifying the alkali solution used to collect the hydrogen chloride after each experiment, evaporating to dryness and testing for aluminum.

It was established by a separate experiment that the mere passage of dry nitrogen at room temperature did not remove any adsorbed hydrogen chloride from aluminum chloride. A fresh sample of aluminum chloride was prepared as before. When all the aluminum had been transformed into chloride, the tube, now full of hydrogen chloride, was cooled to room temperature and both ends closed with pinch cocks; the temperature and pressure were noted. A stream of nitrogen at room temperature was then passed through the tube, and the total hydrogen chloride displaced was determined as described previously. The hydrogen chloride so displaced comprised that present in the tube, and any which had been adsorbed and was driven off by nitrogen at room temperature. The tube was again closed by pinch cocks at room temperature and pressure. The nitrogen in the tube was then expelled by means of a stream of carbon dioxide and collected in a nitrometer over a strong caustic alkali solution to determine the volume of the tube. This was also equal to the

volume of free hydrogen chloride displaced in the first operation. The volume of hydrogen chloride displaced in the first operation was 264.8 cc. and that of nitrogen in the second operation 265.3 cc., showing that no adsorbed hydrogen chloride was evolved from aluminum chloride on passing nitrogen at room temperature for 1.5 hours.

Influence of adsorbed hydrogen chloride on the catalytic activity in the Friedel and Crafts Reaction

The method chosen for a quantitative comparison of the catalytic activity in the Friedel and Crafts reaction was a modification of that used by Rubidge and Qua (2), the amount of hydrogen chloride evolved by the action of benzene and chloroform being measured. A quantity of the ground catalyst was weighed in a tared, dry, 500-cc. flask; the latter was placed in a water bath at room temperature and connected with an upright condenser from which a delivery tube led into a standard alkali solution. A mixture of dry benzene and dry chloroform was added in the proportion of 200 gm benzene and 40 gm chloroform for 30 gm aluminum chloride. When the initial rapid evolution of hydrogen chloride had fallen off, the temperature of the bath was raised to 75-80°C., causing the evolution of hydrogen chloride again to become vigorous. The bath was kept at 80°C. for one hour and was then cooled to room temperature overnight. The excess alkali was titrated. Throughout the experiment nitrogen was passed through the reaction flask at a constant rate.

Concordant results were obtained by this procedure as shown in Table I. The results tabulated here were obtained in three experiments run side by side with different portions of the same batch of aluminum chloride.

TABLE I

MEASUREMENT OF ACTIVITY IN TERMS OF HYDROGEN CHLORIDE EVOLVED

Experiment No.	$AlCl_3$ used, in grams	HCl evolved, in cc. at N. T. P.	HCl per gram of $AlCl_3$, in cc. at N. T. P.
1	21.63	12,868	595
2	21.05	12,451	592
3	20.18	11,826	586

Two samples of aluminum chloride were then prepared by the action of dry hydrogen chloride on aluminum, and the adsorbed hydrogen chloride on one of them was expelled by sublimation in nitrogen in the manner previously described. The catalytic activity of the samples was measured by the procedure just described. The results are given in Table II.

TABLE II

COMPARISON OF THE CATALYTIC ACTIVITY OF $AlCl_3$ WITH AND WITHOUT ADSORBED HCl

Sample	$AlCl_3$ used, in grams	HCl evolved, in cc. at N. T. P.	HCl per gram of $AlCl_3$, in cc. at N. T. P.
$AlCl_3$ with adsorbed HCl	17.402	9,877	568
$AlCl_3$ without adsorbed HCl	15.352	9,380	611

Comparison of the activity of various catalysts

Following the procedure described in the preceding section, the activity of the following catalysts was compared: (1) anhydrous aluminum chloride made by the action of hydrogen chloride on aluminum; (2) anhydrous aluminum chloride made by the action of chlorine on aluminum; (3) anhydrous ferric chloride made by the action of chlorine on iron; (4) the partial reduction product obtained by subliming anhydrous ferric chloride several times in hydrogen at 350° C.; (5) a mixture of (2) and (3); (6) a mixture of (2) and (4). The proportion of the benzene-chloroform mixture applied to the gram-moles of catalyst used was constant. The results obtained are summed up in Table III.

TABLE III

COMPARATIVE ACTIVITY OF CATALYSTS IN THE FRIEDEL AND CRAFTS REACTION

Experiment No.	Catalyst	Amount of catalyst, in moles	Amount of benzene-chloroform mixture, in cc.	Hydrogen chloride evolved in 90 hr, in cc. at N. T. P.	Hydrogen chloride evolved in 90 hr per 0.140 mole catalyst, in cc. at N. T. P.	Relative activity of catalyst in terms of HCl evolved per gram-mole of catalyst
1	$AlCl_3$ (from Al and HCl)	0.085	97	4318	7123	98.6
2	$AlCl_3$ (from Al and Cl_2)	0.140	160	6653	6653	92.1
3	$FeCl_3$ (from Fe and Cl_2)	0.134	157	2625	2742	38.0
4	Ferric chloride (partly reduced)	0.116	136	1093	1324	18.3
5	Mixture of 0.079 moles of No. 2 and 0.081 moles of No. 3	0.160	184	8236	7223	100.0
6	Mixture of 0.068 moles of No. 2 and 0.072 moles of No. 4	0.140	152	6230	6230	86.3

The mixture (Experiment No. 5) of aluminum and ferric chlorides, as may readily be calculated, produced 55% more hydrogen chloride than would have been expected from the components acting separately. Similarly, the mixture (Experiment No. 6) of aluminum chloride and partially reduced ferric chloride yielded a quantity of hydrogen chloride 59% greater than that calculated from the separate activities of the components.

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I. REFLECTION OF SOUND ENERGY AND THICKNESS OF PLATE REFLECTOR—ULTRASONIC METHOD[1]

BY R. W. BOYLE[2] AND D. K. FROMAN[3]

Abstract

The work is an amplification of the method introduced previously by Boyle and Lehmann, and illustrates the application of the theory of monochromatic interference spectroscopy of optics to sound. By experiments with lead, duralumin and paraffin, at different high frequencies, the effects of both high and low reflecting powers are shown, and also the possible influences of harmonics. It is also shown that in travelling through thin discs the velocity of the waves is given more accurately by the bulk modulus of elasticity than by Young's.

Introduction

Ultrasound readily lends itself to an experimental study of the relations existing between the amount of sound energy reflected by a reflector and the thickness of the reflecting body; whereas in such a problem sound of ordinary pitch would present many, and in some cases insuperable, difficulties.

The method followed in this investigation and described in detail below was originated by Boyle and Lehmann (2, 3). They, however, investigated the relation only over a range of one-half wave-length, for a frequency of 135,000 cycles per second, in the reflecting material, and used only one material, viz., lead. In the present experiments the study has been advanced over a wider range both in thicknesses and in materials and the relations have been checked at different frequencies.

The problem is to determine the ratio of reflected to incident sound energy of a continuous train of plane waves of sound incident normally upon a partition. The theoretical relations quoted here are taken from a paper by Boyle and Rawlinson (5) giving the details of a mathematical solution suggested in the theory of sound reflection by Lord Rayleigh (8). The mathematical problem there treated may be enunciated as follows:

A train of plane waves of sound travelling in an infinite, homogeneous, medium is incident normally upon a parallel-faced partition of homogeneous material paced in the medium. The partition is infinitely extended but of finite thickness. What proportion of the incident energy is reflected?

The result obtained is expressed in the following relation:

$$R = \frac{\left(\dfrac{V\rho}{V_1\rho_1} - \dfrac{V_1\rho_1}{V\rho}\right)^2}{4\cot^2\dfrac{2\pi l}{\lambda_1} + \left(\dfrac{V\rho}{V_1\rho_1} + \dfrac{V_1\rho_1}{V\rho}\right)^2}$$

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Contribution from the laboratories of the University of Alberta, Edmonton, Canada, with financial assistance from the National Research Council of Canada.
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Where, R is the ratio of incident to reflected energy density,
V = the velocity of sound in the incident medium,
V_1 = the velocity of sound in the material of the partition,
ρ = the density of the incident medium,
ρ_1 = the density of the material of the partition,
l = the thickness of the partition, and
λ_1 = the wave length in the partition.

By the principle of the conservation of energy, and neglecting losses, the ratio of the energy transmitted to the incident energy must be $1-R$.

Considering the equation above:

If $l = \frac{n\lambda_1}{2}$ where n is zero or an integer, then $\frac{2\pi l}{\lambda_1} = n\pi$ and $\cot \frac{2\pi l}{\lambda_1} = \pm \infty$; hence $R = 0$. If $l = (2n+1)\frac{\lambda_1}{4}$ where n is zero or an integer, $\frac{2\pi l}{\lambda_1} = (2n+1)\frac{\pi}{2}$, and $\cot \frac{2\pi l}{\lambda_1} = 0$; hence R is a maximum.

The solution indicates, therefore, that if the partition be of thickness zero or an integral number of half wave-lengths in its material, the reflection will be a minimum and the transmission a maximum, and if the thickness be an odd number of quarter wave-lengths the reflection will be a maximum and the transmission a minimum.

The relation also shows that, other things being equal, reflection will be greatest when $\left(\frac{V\rho}{V_1\rho_1} - \frac{V_1\rho_1}{V\rho}\right)$ is a maximum, i.e., when V differs greatly from V_1. The reflection will be zero when $V = V_1$, a fact already used in previous papers on the reflection of ultrasonic waves (7). This relation applies to all thicknesses of partition, and it should hold for all frequencies.

It should be noticed that the reflection is least and transmission greatest when the thickness of the partition is appropriate for longitudinal vibration in resonance with the incident wave train.

The above is an outline of the mathematical theory to test which this research was carried out. The theory is analogous to that of interference spectroscopy in optics, but ultrasonics offers a new means for its experimental investigation.

Experimental Method

The method was the same as that used by Boyle and Lehmann, who employed a torsion pendulum. Ultrasonic energy was generated by the usual type of exciting electrical apparatus and the usual type of piezo-electric

generator, from which the emitted ultrasonic beam was projected down the middle of a large wooden tank, 15 ft. long × 5 ft. wide × 3.5 ft. high, filled with water. The required energy measurements were made by means of a torsion pendulum placed in the path of the beam, the deflections being due to the radiation pressure of the waves in the energy field. The exciting apparatus, tank, pendulum, mountings, and method of use have all been previously described (1, 4). The essential idea of the method is as follows: when a torsion pendulum is placed in the path of an ultrasonic beam projected horizontally, the vertical vane of the pendulum acts as a reflecting obstacle. Since the deflecting pressure at the pendulum depends not only on the incident energy but also on the proportion of the incident energy reflected by the vane, the resultant pressure causing deflection must depend on the ratio of the thickness of the vane to the wave-length of the radiation in its material. Consequently it is possible to interpret the readings of the pendulum to yield information on the factor of the reflection, which is the point of this paper.

Applying the mathematical deductions quoted above, the best thickness, theoretically, to make the pendulum vane is one-quarter wave-length, for at this thickness the reflection is a maximum, and, for most materials, practically total.

If a plane wave train falls on a perfectly reflecting surface, the radiation pressure exerted on the reflector is 2E, where E is the energy density of the incident radiation; if the surface be a perfect absorber, the pressure is E+RE. Consequently a test of the mathematical relation quoted above becomes possible by taking energy observations with pendula vanes, of the same material and area, but with various thicknesses, when they are subjected to ultrasonic radiation under exactly similar conditions. It is obvious that the pendulum reading will depend on the area of the vane; in comparative measurements like the present, however, the areas of the vanes of all the pendula used can be kept the same, so that this factor need not enter into the calculations. Also, any diffraction effect of the waves around the edges of the pendulum is the same for all the vanes when the area is kept identical, and in consequence need not be taken into account. A special research to determine the diffraction effect in the use of torsion pendula of different areas has already been carried out and will be reported in a later paper.

Let the energy density of the incident beam in the pendulum vane be E ergs per cm^3.. and the ratios of the reflected and transmitted energies to the incident be R and T respectively; and let α be the absorption coefficient for the waves in the vane material. Then the pressure on the vane due to incidence and reflection in the direction of the incident energy when the vane is at right angles to the field is (E+RE) dynes per sq. cm. But the transmitted energy T is equal to $(E-RE)e^{-al}$ ergs per cm^3. where l is the thickness of the vane, and due to it the back pressure upon the vane, against that of the incident energy is $(E-RE)e^{-al}$. Hence the resultant pressure on the vane in the direction of incidence is $(E+RE)-(E-RE)e^{-al}$. When the vane is thin

enough that absorption can be neglected this expression reduces to 2RE dynes per sq. cm. Therefore, to maintain the vane perpendicular to the energy field against this pressure the torsional force imposed on the pendulum suspension will be proportional to 2RE, and hence if E remains constant the pendulum readings must be proportional to R.

Experimental Details

The more massive the pendulum the greater its amount of inertia and consequently the longer the period of oscillations and time to come to rest. It is inconvenient and tiresome to work with pendula having periods unduly long, for conditions must be kept steady during the oscillation. The reflecting power (R) of a material depends on the product of its density and the velocity of sound in it (1, 6), while the mass of the vane required for experiment depends on the product of the density and wave-length. A list of possible and convenient materials for experiment was drawn up and relevant factors concerning them set out in Table I.

TABLE I

RELATIVE MASS PER WAVE-LENGTH

Substance	Bulk modulus of elasticity in dynes per cm^2.	Density in grams per cm^3.	Velocity of sound, $V = E$ per cm. per sec.	Relative mass per wave-length, in grams
Paraffin	0.115×10^{11}	0.90	1.30×10^5	1.18×10^5
Water	0.220×10^{11}	1.00	1.48×10^5	1.48×10^5
Magnesium	4.32×10^{11}	1.74	4.98×10^5	8.67×10^5
Antimony	1.67×10^{11}	6.62	1.59×10^5	10.5×10^5
Glass	3.6 to 6.0×10^{11}	2.8(approx.)	3.6 to 4.6×10^5	10 to 13×10^5
Duralumin	7.5×10^{11}	2.79	5.16×10^5	14.4×10^5
Bismuth	3.14×10^{11}	9.80	1.79×10^5	17.5×10^5
Cadmium	4.12×10^{11}	8.64	2.19×10^5	18.8×10^5
Tin	5.29×10^{11}	7.29	2.70×10^5	19.6×10^5
Lead	5.00×10^{11}	11.4	2.09×10^5	23.8×10^5
Brass	10.7×10^{11}	8.44	3.50×10^5	29.5×10^5
Copper	14.3×10^{11}	8.93	4.00×10^5	35.7×10^5
Nickel	17.6×10^{11}	8.90	4.50×10^5	39.1×10^5
Steel	18.1×10^{11}	7.7 to 7.9	4.81×10^5	37.8×10^5

A glance at the table will show the materials most suitable for use. Any material with product $V\rho$ greater than that of lead would be inconveniently heavy for these experiments. Metallic magnesium would have been very suitable but for the fact that it is affected chemically in the water and a layer of gas bubbles forms on its surface. After considering the availability and ease of working of the different materials, lead, duralumin, and paraffin were selected. The lead and duralumin were well separated in the metals in the last column of Table I and had high reflecting powers; paraffin was specially included as being a substance possessing such elastic qualities that its reflecting power must be low. The experiments later showed anomalies in paraffin and brought out difficulties in its use.

A number of pendula of various thicknesses were made from each of the materials named. It was, of course, necessary to work under steady conditions of energy emission, and it was desirable to make the energy field as nearly uniform over the face of the pendulum as possible. It was also desirable to work with such high frequencies that the desired number of wave-lengths in thickness could be obtained without the pendula vanes becoming too massive.

The ultrasonic generator, a double-steel-plate instrument, was chosen because it adapted itself to these experimental requirements. Its radiating face was of small diameter, viz., 10 cm., so that the emitted beam was fairly wide for the high frequencies of the experiments. (Angle of spread of the emitted beam (approximately) $=1.22\mathrm{D}\frac{\lambda}{\mathrm{D}}$ where λ is the emitted wave-length and D is the diameter (1, 4)). By determining experimentally the "characteristic", energy emission, curve of the generator two suitable overtone resonant frequencies were discovered, at 531,200 and 307,200 cycles per second. At these frequencies the emission curve was not very sharp, but fairly rounded which meant that energy emission would change only very slightly for small changes in frequency. Moreover at these frequencies an electric wave-meter, employed as an accessory to measure the frequency, showed that any additional electrical harmonics present could not have been of appreciable magnitude.

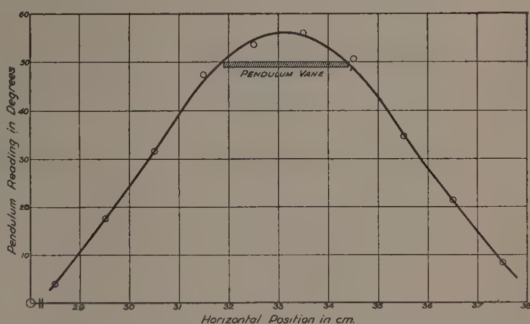


FIG. 1. *Cross sectional survey of the energy field (frequency= 531,200 cycles per sec.). The relative position of the pendulum vane is indicated.*

Although in reflection the ratio of reflected to incident energy does not depend on any variation of incident intensity over the reflecting surface, nevertheless it is better to work with an incident field as nearly uniform as possible over the reflecting pendulum vane. Energy surveys, vertically and horizontally in a cross-section of the energy field, were carried out, and the pendulum vane then suspended at the position of maximum energy of the section so found. The consequence was that even at the higher quoted frequency of experiment, when the beam is narrower than at the lower, the variation of incident intensity over the pendulum face diminished only about 12% from the centre to the rim. Fig. 1 indicates the cross sectional survey of the energy field at the frequency of 531,200 cycles per second, with the relative position of pendulum vane also indicated.

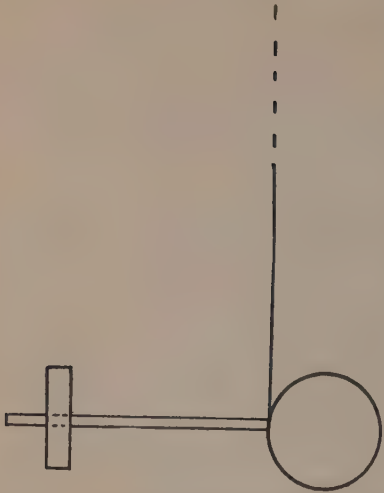


FIG. 2. *Counter-balanced type of pendulum used.*

Instead of using a "double-vane" pendulum, as did Boyle and Lehmann (3), a pendulum of the "counter-balance" type was employed. This type is indicated by the diagram, Fig. 2, which explains itself. The effect of the radiation pressure on the area of the counterweight exposed to the radiation, acting against that on the vane, was only a small percentage of the latter and within the experimental error of the work.

Results

WITH LEAD REFLECTOR

The generator was first set to oscillate at a frequency of 531,200 cycles per second, which frequency was maintained constant. A series of lead pendula, all of the same diameter, viz., 2.50 cm., but of different thicknesses, were successively suspended by the same phosphor-bronze wire, 0.003 in. in diameter, into the same position on the axis of the ultrasonic beam, under identical conditions of excitation. Pendulum readings were taken in each case. After

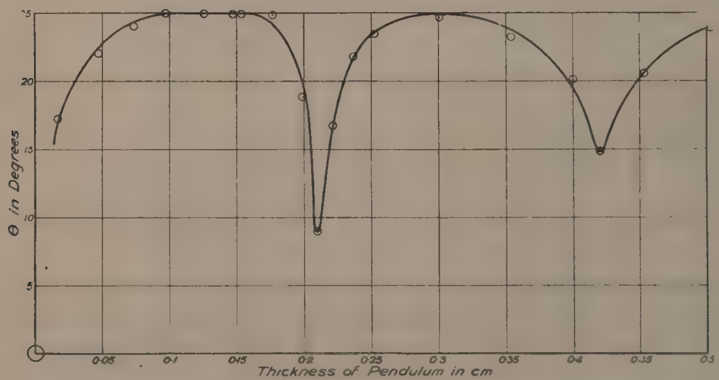


FIG. 3. *Relation of deflection to corresponding thickness of pendulum vane.*

every two or three sets of readings some one pendulum, used as a standard, was replaced in the beam to determine if the energy emission of the transmitter had remained constant. If it had changed slightly, the necessary correction

could be made by taking the ratio of the other pendulum readings to that of the standard. Generally the emitted energy was found to be constant within a few percent. The pendulum readings with the corresponding thickness of pendulum vane are given in Table II, and the readings plotted against the thickness in Fig. 3.

TABLE II

THICKNESS OF PENDULUM AND CORRESPONDING DEFLECTION AT FREQUENCY OF 531,200 CYCLES

Thickness of pendulum vane, in cm.	Pendulum reading, in degrees	Thickness of pendulum vane, in cm.	Pendulum reading, in degrees
0.016	17.2	0.210	8.9
0.048	22.0	0.236	21.8
0.074	24.0	0.252	23.4
0.097	25.0	0.301	24.6
0.125	24.9	0.355	23.1
0.148	24.9	0.400	20.1
0.152	25.0	0.420	14.8
0.176	24.8	0.453	20.5
0.198	18.8	0.503	23.8

It will be striking that there are two well marked dips in the curve where the reflection ratio is very low. By considering the theory outlined in the introduction of this paper it will be concluded that these dips occur at or near thicknesses of exact half wave-lengths of the ultrasound in the material of the pendulum. Consequently, examining the curve, we may say that 0.21 cm. was *one* half-wave-length at a frequency of (near) 531,200 cycles per second and 0.42 cm. was *two* half-wave-lengths at the same frequency. Hence the velocity in lead was $0.42 \times 531{,}200 = 2.23 \times 10^5$ cm. per sec.

Another method of experiment to determine the velocity, by disclosing the exact frequency at which the thickness of pendulum vane is an integral number of half-wave-lengths, was carried out as follows: A pendulum of the correct thickness to yield the maximum deflection at the energy emission of the experiment was employed to take a "characteristic", energy emission curve, over a range of frequencies at and near the operating frequency of 531,200 cycles per second. The deflections so obtained were plotted against the frequency. The readings are given in Table III and plotted against frequency in Fig. 4 (curve 1). Then the pendulum which gave the lowest reading (nearest the bottom of the first dip) in the deflection-thickness curve, Fig. 3, that is, the pendulum nearest to a half-wave-length in thickness, was used to obtain a characteristic, energy emission curve over the same frequency range: Table III, Fig. 4 (curve 2). By adjusting the frequency carefully a value can be found at which this pendulum vane is exactly a half-wave-length in

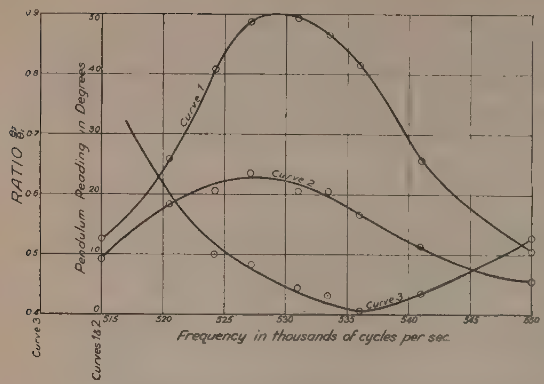


FIG. 4. *Relation of pendulum deflections to corresponding frequencies.*

thickness; for, at this frequency, the ratio of the reading of this pendulum to that of the first will be a minimum. These ratios are given in Table III and plotted against frequency in Fig. 4 (curve 3). From curve 3 it appears that the minimum ratio occurred with a thickness of vane of 0.21 cm., at a frequency of 536,000 cycles per second exactly; it therefore follows that the wave-length at this frequency was 0.42 cm., and hence the velocity was 2.23×10^5 cm. per sec. This value of the velocity is near that determined by Boyle and Lehmann (3), viz., 2.06×10^5 cm. per sec., and much higher than the values quoted for low frequency sound, (e.g., 1.23×10^5 cm. per sec.) as determined by computations from static experimental methods. The result of this experiment is a confirmation of the result obtained by the former method where many pendula of various thicknesses were employed.

TABLE III

DEFLECTIONS OF A PENDULUM FOR GIVEN FREQUENCIES

Frequency, in cycles per second	Deflection of vane giving maximum reading, θ_1, in degrees	Deflection of vane near $\frac{\lambda_1}{2}$ in thickness, θ_2, in degrees	Ratio of readings, $\frac{\theta_2}{\theta_1}$
515000	12.8	9.0	0.704
520500	26.0	18.3	0.705
524300	40.8	20.4	0.500
527200	48.8	23.5	0.482
531000	49.5	20.8	0.444
533500	46.5	20.5	0.430
536000	41.2	16.6	0.403
541000	25.6	11.1	0.435
550000	10.5	5.5	0.524

From the mathematical relation quoted in the introduction of this paper a theoretical curve of the reflection ratio R against various ratios of thickness to wave-length $\left(\frac{l}{\lambda_1}\right)$ can be computed, as has been done in Table IV, and plotted as in Fig. 5, curve 1. Here the value of the velocity in lead as determined in the present experiments has been employed.

TABLE IV

THEORETICAL REFLECTION COEFFICIENTS FOR VARIOUS THICKNESS RATIOS*

$\frac{l}{\lambda_1}$	$4 \cot^2 \frac{2\pi l}{\lambda_1}$	R	$\frac{l}{\lambda_1}$	$4 \cot^2 \frac{2\pi l}{\lambda_1}$	R
0.00	∞	0.000	0.20	0.422	0.986
0.01	1011	0.222	0.25	0.	0.987
0.015	450	0.389	0.30	0.422	0.986
0.02	251	0.532	0.34	1.61	0.980
0.025	159	0.639	0.40	7.62	0.961
0.03	110	0.717	0.45	37.9	0.874
0.04	60.7	0.817	0.47	110	0.717
0.05	37.9	0.874	0.475	159	0.639
0.06	25.6	0.906	0.48	251	0.532
0.08	13.2	0.944	0.485	450	0.389
0.10	7.62	0.961	0.49	1011	0.222
0.16	1.61	0.980	0.50	∞	0.000

*Velocity of sound in lead, $V_1 = 2.33 \times 10^5$ cm. per sec.
Velocity of sound in water, $V = 1.48 \times 10^5$ cm. per sec.
Density of lead, $\rho_1 = 11.3$ grams per cm³.
Density of water, $\rho = 1.00$ gram per cm³.
Frequency used, 531,200 cycles per second.

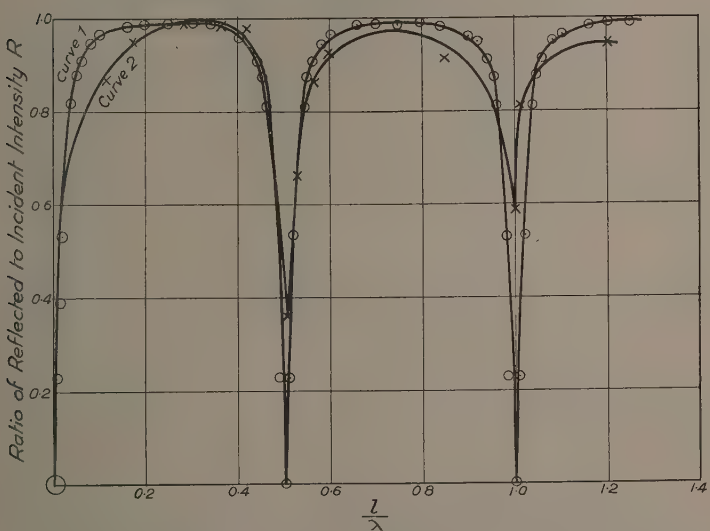


FIG. 5. *Relation of the ratio of reflected to incident energy and the ratio of thickness of pendulum to wave-length. Plotted from theoretical values in curve 1 and experimental results in curve 2. (Lead pendulum).*

It should be pointed out that at any thickness which is an integral number of half-wave-lengths the radiation pressure on the face of the reflector is theoretically equal to, and balanced by, the back pressure on the reverse face of the reflector due to the transmitted energy. These are the thicknesses for

longitudinal resonance, and at such thicknesses, theoretically, we can imagine the reflector picking up the energy on the incident side and re-emitting it in equal quantity at the opposite face. But there is certain to be a little absorption and other possible losses, so that the transmitted energy will be less than the incident, and therefore the pendulum readings at these thicknesses will be a series of minima rather than zero. These minima should rise with increasing thickness. Using the highest pendulum reading obtained to correspond to the maximum value of R, those values of R which corresponded to the pendulum readings at the various thicknesses of vane were computed (Table V), and plotted in Fig. 5, curve 2. Curves 2 and 1 in Fig. 5 compare the results of experiment with those derived from theory.

TABLE V

EXPERIMENTAL REFLECTION COEFFICIENTS FOR VARIOUS THICKNESS RATIOS*

Thickness of pendulum (l), in cm.	$\frac{l}{\lambda_1}$	Pendulum reading (θ), in degrees	$R\left(=\frac{0.987}{25}\theta\right)$
0.016	0.038	17.2	0.679
0.048	0.114	22.0	0.869
0.074	0.176	24.0	0.948
0.097	0.231	25.0	0.987
0.125	0.298	24.9	0.984
0.148	0.352	24.9	0.984
0.152	0.362	25.0	0.987
0.176	0.419	24.8	0.980
0.198	0.472	18.8	0.742
0.210	0.500	8.9	0.352
0.236	0.562	21.8	0.861
0.252	0.600	23.4	0.925
0.301	0.717	24.6	0.972
0.355	0.845	23.1	0.912
0.400	0.954	20.1	0.795
0.420	1.000	14.8	0.584
0.453	1.080	20.5	0.810
0.503	1.200	23.8	0.940

**Maximum pendulum reading 25.0° corresponds to maximum value of R (0.987) in the theoretical curve, as computed =0.42 cm.*
Frequency used, 531,200 cycles per second (lead reflector).

A second set of experiments with lead pendula and at the same frequency, but with a new phosphor-bronze wire suspension, 0.0025 cm. in diameter, was carried out. The resulting curve for the reflection ratio was very nearly a repetition of the experimental curve already shown and therefore is not included here.

Similar experiments to all the above were carried out with lead vanes but at a different frequency, viz., 307,200 cycles per second. The observations are given in Table VI, but the curves are not shown since they are similar to those at the first frequency and have no additional interest. The velocity determined at this frequency was 2.23×10^5 cm. per second.

TABLE VI

DEFLECTION OF PENDULUM AND CORRESPONDING THICKNESS OF VANE*

Thickness of pendulum vane, in cm.	Pendulum readings, in degrees	Thickness of pendulum vane, in cm.	Pendulum readings, in degrees
0.016	26.5	0.355	25.1
0.047	44.2	0.367	15.7
0.097	47.7	0.378	22.9
0.176	47.7	0.400	29.6
0.252	45.3	0.419	37.5
0.301	37.9	0.502	40.8
0.332	29.8		

**Frequency used, 307,200 cycles per sec. (Lead reflector).*

The velocity determined from the results of all the experiments on lead was as follows:

At a frequency of 531,200 cycles per sec. $\begin{cases} \text{by the first method } 2.23 \times 10^5 \text{ cm. per sec.} \\ \text{by the second method } 2.25 \times 10^5 \text{ cm. per sec.} \end{cases}$

At a frequency of 307,200 cycles per sec. $\begin{cases} \text{by the first method } 2.25 \times 10^5 \text{ cm. per sec.} \\ \text{by the second method } 2.21 \times 10^5 \text{ cm. per sec.} \end{cases}$

Mean 2.23×10^5 cm. per sec.

WITH DURALUMIN REFLECTOR

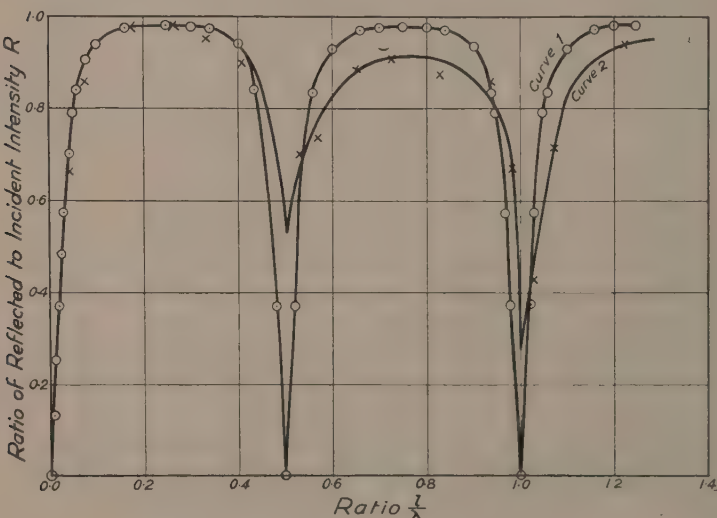
The entire process was repeated using duralumin vanes instead of lead. To economize space all the details of the results obtained are not shown here, but as typical a few of these are included below. In Table VII are given the theoretical values of R for the various values of $\left(\frac{l}{\lambda_1}\right)$, using the value of velocity in duralumin as determined in the experiments. In Table VIII the pendulum observations at the frequency 531,200 cycles per second are given and in Table IX those at 307,200 cycles per second. Corresponding curves are shown in Fig. 6 and Fig. 7, curves 1 and 2 respectively.

TABLE VII

THEORETICAL REFLECTION COEFFICIENTS FOR VARIOUS THICKNESS RATIOS*

$\frac{l}{\lambda_1}$	$4 \cot^2 \frac{2\pi l}{\lambda_1}$	R	$\frac{l}{\lambda_1}$	$4 \cot^2 \frac{2\pi l}{\lambda_1}$	R
0.00	∝	0.000	0.20	0.422	0.974
0.01	1011	0.128	0.25	0.000	0.977
0.015	450	0.248	0.30	0.422	0.974
0.02	251	0.370	0.34	1.61	0.968
0.025	159	0.479	0.40	7.62	0.931
0.03	110	0.569	0.45	37.9	0.784
0.04	60.7	0.700	0.47	110	0.569
0.05	37.9	0.784	0.475	159	0.479
0.06	25.6	0.838	0.48	251	0.370
0.08	13.2	0.900	0.485	450	0.248
0.10	7.62	0.931	0.49	1011	0.128
0.16	1.61	0.968	0.50	∝	0.000

*The velocity of sound in duralumin, $V_1 = 6.48 \times 10^5$ cm. per sec.
The velocity of sound in water, $V = 1.48 \times 10^5$ cm. per sec.
The density of duralumin, determined experimentally, $\rho_1 = 2.81$ gm. per cm^3.
The density of water, $\rho = 1.0$ gm. per cm^3.
Frequency used, 531,200 cycles per second (duralumin reflector).



'G. 6. *Relation of the ratio of reflected to incident energy and the ratio of thickness to wave-length. Plotted from theoretical values in curve 1 and experimental results in curve 2. (Duralumin pendulum; frequency 531,200 cycles per sec.).*

TABLE VIII

EXPERIMENTAL REFLECTION COEFFICIENTS FOR VARIOUS THICKNESS RATIOS*

Thickness of pendulum vane, in cm.	$\frac{l}{\lambda_1}$	Pendulum reading, in degrees	R $\left(= \frac{0.977}{26.9}\ \theta\right)$
0.052	0.0426	18.1	0.657
0.090	0.0738	23.6	0.858
0.203	0.166	27.0	0.977
0.300	0.246	26.9	0.977
0.405	0.332	26.0	0.945
0.496	0.406	24.6	0.894
0.598	0.490	16.7	0.606
0.652	0.535	19.2	0.698
0.699	0.574	20.1	0.730
0.802	0.657	24.3	0.884
0.896	0.735	24.9	0.905
1.002	0.836	24.0	0.872
1.145	0.939	23.2	0.843
1.202	0.987	18.5	0.672
1.252	1.03	11.6	0.421
1.302	1.07	19.7	0.716
1.499	1.23	25.7	0.934

**Maximum pendulum reading, 26.9°, corresponds to maximum value of R (0.977) in the theoretical curve.* $\lambda_1 = 1.22$ *cm.*

Frequency used, 531,200 cycles per second (duralumin reflector).

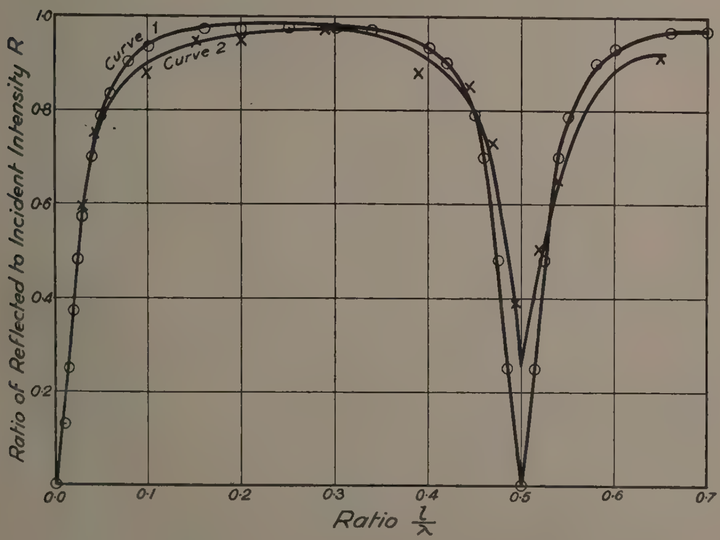


FIG. 7. *Relation of the ratio of reflected to incident energy and the ratio of thickness of pendulum to wave-length. Plotted from theoretical values in curve 1 and experimental results in curve 2. (Duralumin pendulum; frequency 307,200 cycles per sec.).*

TABLE IX

EXPERIMENTAL REFLECTION COEFFICIENTS FOR VARIOUS THICKNESS RATIOS*

Thickness of pendulum vane, in cm.	$\frac{l}{\lambda_1}$	Pendulum reading, in degrees	$R\left(=\frac{0.977}{56.9}\theta\right)$
0.052	0.0257	34.8	0.598
0.090	0.0446	43.2	0.742
0.202	0.100	51.1	0.897
0.298	0.148	56.1	0.965
0.405	0.200	55.0	0.946
0.597	0.296	56.9	0.977
0.801	0.396	51.2	0.880
0.896	0.444	49.2	0.846
0.950	0.470	42.3	0.727
1.002	0.497	22.5	0.387
1.051	0.521	29.2	0.502
1.099	0.544	38.6	0.664
1.302	0.645	53.3	0.917

**Maximum pendulum reading, 56.9°, corresponds to the maximum value of R, 0.977, in the theoretical curve. $\lambda_1 = 2.02$ cm.*
Frequency used, 307,200 cycles per second (duralumin reflector).

The values of velocity as computed from the results were as follows:

At 531,200 cycles per sec. $\begin{cases} \text{by the first method } 6.43 \times 10^5 \text{ cm. per sec.} \\ \text{by the second method } 6.50 \times 10^5 \text{ cm. per sec.} \end{cases}$

At 307,200 cycles per sec. $\begin{cases} \text{by the first method } 6.21 \times 10^5 \text{ cm. per sec.} \\ \text{by the second method } 6.27 \times 10^5 \text{ cm. per sec.} \end{cases}$

Mean 6.35×10^5 cm. per sec.

These values of velocity in duralumin are considerably higher than the values quoted for low frequency sound in the same material and estimated from the physical constants of density and elastic modulus as determined by static experimental methods. For example, a quoted velocity in duralumin is 5.13×10^5 cm. per sec.

To find what value static experimental methods would give, with the same material as here used, Young's modulus and the density of a sample of the material were determined. The modulus was taken by a tension test in a Buckton testing machine[1]. The results were:

Young's modulus of duralumin, $E = 7.40 \times 10^{11}$ dynes per sq. cm.,
density, $\rho_1 = 2.79$ gm. per cm^3.

Hence the velocity should be $V_1 = \sqrt{\frac{E}{\rho_1}} = 5.16 \times 10^5$ cm. per sec., which is in good agreement with the values quoted for low frequency sound.

[1] *We are obliged to Professors Morrison and Cameron for making this test.*

With Paraffin Reflector

Paraffin was specially chosen, the interest in it being that its reflecting power is low, since the product of the density of paraffin and the velocity of sound in it is nearly equal to the product of these factors for water. Much trouble was experienced with pendula made of solid paraffin, which proved to be a most unsatisfactory material with which to deal.

However, the work brought out some very interesting points. For instance, a series of paraffin pendula could be used, and the readings plotted against thickness of vane as described above; then, on repeating the series some time later, a totally different curve would result. It was found, however, that consistent results could be obtained if the work were done very rapidly under constant conditions. Changes of temperature were found especially to affect the readings. The elasticity of paraffin changes rapidly with the temperature around 12°C. or 15°C., and consequently the velocity of sound in this substance varies rapidly as the temperature changes. Paraffin is a good heat insulator; a pendulum of considerable thickness, kept in the air say at 20°C. and then placed in the water at about 12°C., will not take up the temperature of the water throughout its mass for some time, and as far as its acoustic properties are concerned, will not be homogeneous. A thin pendulum will, of course, take up more quickly the surrounding temperature. By keeping the paraffin pendula completely in the water of the tank instead of in the air of the laboratory, prior to an experiment, and by conducting the series of experiments very rapidly, before the temperature of the water could change appreciably, consistent results could be obtained.

TABLE X

Deflection of pendulum and corresponding thickness of vane*

Thickness of pendulum vane, in cm.	Pendulum reading, in degrees	Thickness of pendulum vane, in cm.	Pendulum reading, in degrees
0.097	23.5	0.525	86.2
0.154	45.1	0.566	74.0
0.215	48.0	0.610	75.0
0.248	41.6	0.645	69.5
0.305	27.7	0.652	75.0
0.365	29.2	0.700	69.6
0.383	33.3	0.739	90.4
0.456	59.2	0.793	89.4
0.487	73.5		

**Frequency used, 307,200 cycles per second (paraffin reflector).*

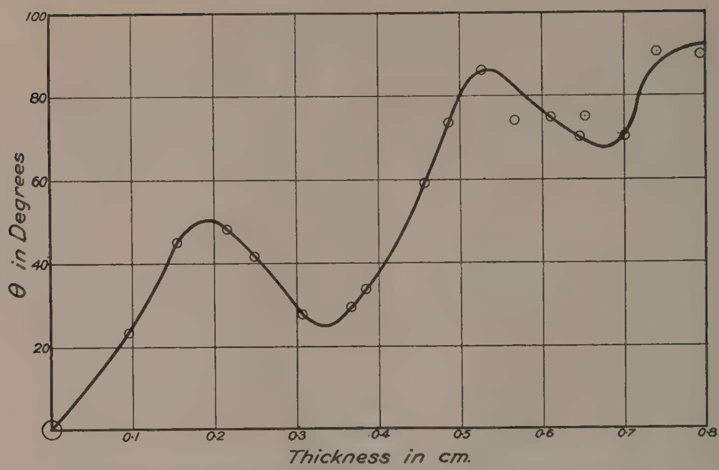


FIG. 8. *Relation of deflection to thickness with paraffin pendula. (Frequency, 307,200 cycles per sec.).*

TABLE XI

THEORETICAL REFLECTION COEFFICIENTS FOR VARIOUS THICKNESS RATIOS*

$\frac{l}{\lambda_1}$	$4\cot^2\frac{2\pi l}{\lambda_1}$	R	$\frac{l}{\lambda_1}$	$4\cot^2\frac{2\pi l}{\lambda_1}$	R
0	$\propto$	0.00000	0.20	0.422	0.0508
0.01	1011	0.00023	0.25	0	0.0559
0.02	251	0.00093	0.30	0.422	0.0508
0.03	110	0.00207	0.34	1.61	0.04050
0.04	60.7	0.00364	0.40	7.62	0.02051
0.05	33.9	0.00620	0.47	110	0.00207
0.06	25.6	0.00793	0.475	159	0.00145
0.08	13.2	0.01358	0.48	251	0.00093
0.10	7.26	0.02051	0.49	1011	0.00023
0.16	1.61	0.04050	0.50	$\propto$	0.00000

*$V = 1.48 \times 10^5$ *cm. per sec.*
$V_1 = 2.09 \times 10^5$ *cm. per sec.*
$\rho = 1$ *gram per cm*^{3}.
$\rho_1 = 0.901$ *grams per cm*^{3}.
Frequency used 307,200 cycles per second (paraffin reflector).

A series of paraffin pendula readings were taken with the ultrasonic generator operating at a frequency of 307,200 cycles per second, and on checking were found to be consistent. Fig. 8, constructed from Table X, shows the deflections plotted against the thickness of the pendulum. The half-wave-length is about 0.34 cm. at a frequency of 307,200 cycles per second. Hence the velocity of the sound was $2 \times 0.34 \times 307{,}200 = 2.09 \times 10^5$ cm. per sec. The density of the paraffin was determined and found to be 0.9 gm. per cm^3. Using hese values, the theoretical curve of R against $\frac{l}{\lambda_1}$ was plotted (curve 1) in

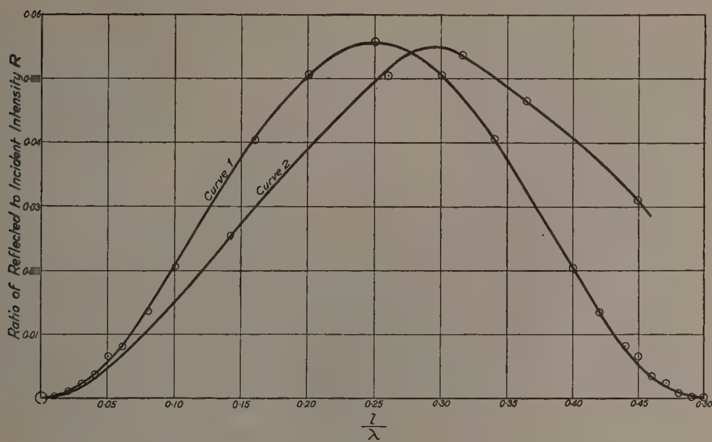


FIG. 9. *Relation of the ratio of reflected to incident energy and the ratio of thickness of pendulum to wave-length. Plotted from theoretical values in curve 1 and experimental results in curve 2. (Paraffin pendulum).*

Fig. 9, from the computed values in Table XI. It should be noticed that this curve is not nearly so blunt as in the cases of metals, since the reflecting power of paraffin is relatively low. The highest reading in the first half-wave-length only, Table X, was taken as corresponding to the maximum value of R, and, with 0.68 cm. as wave-length, the readings for the first half-wave-length only were reduced to ratios in Table XII, and plotted, in curve 2, Fig. 9. The quoted value for the velocity in paraffin of low frequency sound, viz., 1.30×10^5 cm. per sec. is in this case, as well as in the case of the metals, much lower than the observed value.

TABLE XII

EXPERIMENTAL REFLECTION COEFFICIENTS FOR VARIOUS THICKNESS RATIOS*

Thickness of pendulum vane, in cm.	Pendulum reading (θ), in degrees	$\frac{l}{\lambda_1}$	$R\left(=\frac{0.056}{50}\theta\right)$
0.097	23.5	0.14	0.025
0.154	45.1	0.23	0.050
0.215	48.0	0.32	0.054
0.248	41.6	0.37	0.047
0.305	27.7	0.50	0.031
0.365	29.2	0.54	0.033

**Maximum deflection in first loop $=50°$, and corresponds to $R=0.056$. $\lambda_1=0.68$ cm. Frequency used, 307,200 cycles per second (paraffin reflector).*

It will be noticed that in the curve of pendulum reading plotted against thickness of vane (Fig. 8) the second loop rises much higher than the first. This was found to be always the case with paraffin; in one case three loops

were obtained, the second higher than the first and the third higher than the second. An explanation can readily be conceived. The reflecting power of paraffin is relatively low since the product of its density and the wave-length of the sound in it is very nearly equal to the same product for water, and, as shown in the preceding theory, this would cause a low reflection. In consequence its transmitting power is relatively high and back pressure on the pendulum vane appreciable. As the thickness of the paraffin vane is increased, absorption of ultrasound in it is increased also, thus reducing the transmitted energy and back pressure. Hence as the thickness of vane was increased the recoil pressure due to the transmitted energy became smaller, which, of course, caused a greater resultant pendulum reading. Such conditions would not appear in metallic reflection, since, in general, most of the incident energy would be reflected even by pendula less than a quarter wave-length thick, and the difference caused by absorption in the small amount of energy transmitted would not be large enough to make an appreciable difference in the observations.

Effect of Harmonics

The effects of harmonics should be more marked with materials such as paraffin, in which the velocity and the reflecting power are low. In such cases the wave-length is relatively short, so that even a thin pendulum may have a thickness near an odd number of quarter wave-lengths for a higher frequency harmonic. Also the emitted ultrasonic beam of a harmonic must be narrower and, therefore, its energy more concentrated than in the beam of the fundamental, since the angle of the beam depends on $\frac{\lambda}{D}$. Accordingly, it was considered advisable to see if the effects of harmonics could be detected in the phenomenon with paraffin.

A different generator to emit a larger wave-length was employed and was set oscillating at a lower frequency than any previously used, viz., 163,200 cycles per second. Two prominent electrical harmonics were present in the electrical oscillation circuits, the energy of each being about 30% of that of the fundamental, as indicated by a measuring wave meter. There was no means of detecting possible additional harmonics of a mechanical nature in the mechanical oscillation of the generator.

A series of pendulum readings with vanes of many thicknesses was taken at the above frequency as fundamental. The curves so obtained were highly irregular, no matter how stable the experimental conditions could be kept.

Not much more could be concluded from the analysis of these curves than the general fact that the harmonics had a marked effect on the phenomenon, as shown by the deflections, which made it almost impossible to sort out their influence from that of the fundamental. Fig. 10 shows as an example one of the curves obtained. According to the velocity determination made above,

the second dip in this curve corresponds to one half-wave-length thickness of the paraffin, the other dips and extra peaks are undoubtedly due to some combination of harmonics, perhaps mechanical, in the generator as well as electrical in the circuits.

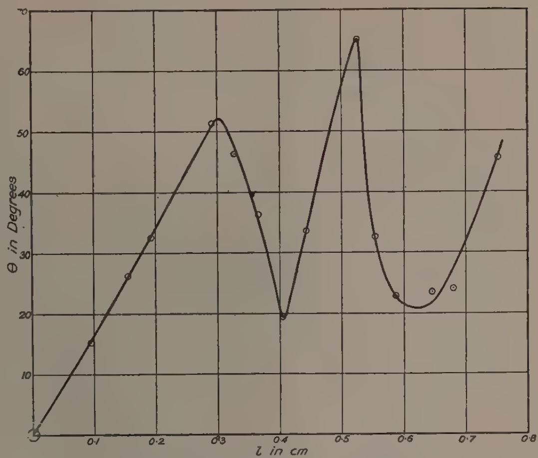


FIG. 10. *Relation of deflection to thickness of paraffin pendula.* (*Frequency, 163,200 cycles per sec.*).

In all the experiments described in this paper the determined velocities have come out to be significantly higher than the velocity quoted for the same materials by low frequency methods. The explanation lies in the fact that the latter are almost invariably deduced from experiments, with rods or bars of the material, depending on a determination of Young's modulus of elasticity.

The relation $V=\sqrt{\frac{E}{\rho}}$, where E is Young's modulus, for a rod for example, is based on the assumption that the length of the rod (l) is many times the radius (r), e.g., in the ordinary Kundt's tube $\frac{r}{l}$ may be $\frac{1}{150}$ or $\frac{1}{200}$. But with the thin discs (pendulum vanes) used in these ultrasonic experiments the radius is large in comparison with the length, or the ratio $\frac{r}{l}$ is much higher than 1.

For an infinite medium the velocity is given more correctly by the relation $V=\sqrt{\frac{K}{\rho}}$, where K is in the bulk modulus, instead of Young's. In such a case the velocity also is given in the relation $V^2=\frac{1-\sigma}{(1+\sigma)\,(1-2\sigma)}\times\frac{E}{\rho}$ where σ is Poisson's ratio. If for duralumin the value 0.36 is taken for σ, the determined value 7.4×10^{11} for E, and 2.79 for ρ, the value of the velocity in an infinite medium of the material is 6.8×10^5 cm. per sec. This is much nearer the value 6.5×10^5 cm. per sec. found in these ultrasonic experiments.

It is evident that in theoretical and practical considerations by the present ultrasonic method the bulk modulus rather than Young's will give results more nearly correct, and for still greater accuracy definite account should be taken of the value of the ratio.

Conclusions

From the results obtained by the use of lead, duralumin, and paraffin torsion pendula of various thicknesses in an ultrasonic beam, it can be concluded that:

(1) The theory outlined in this paper, although developed for a reflector of finite thickness and infinite extension, does fairly well indicate what actually takes place in reflection from, and transmission through, a reflector of finite dimensions. It should be noticed that the linear dimensions of the reflectors used were of the order of a wave-length. Undoubtedly the reflection is a maximum and transmission a minimum for thicknesses equal to an odd number of quarter wave-lengths, and reflection a minimum and transmission a maximum for thicknesses equal to an integral number of half-wave-lengths.

(2) The theory outlined contains no terms for absorption of the sound energy in the material of the partition. It has been shown however that in the case of paraffin, which is relatively a poor reflector of the ultrasonic energy, the effect of absorption can be demonstrated. As has been pointed out, the effect does not markedly appear in the cases of the metals since their reflecting power is so high that usually little energy can be transmitted. Therefore, any changes in the transmission due to absorption are not appreciable.

(3) In the three materials used the reflection ratio, R, at a thickness of one fourth wave-length is higher the greater the difference between the products of density and wave-length for the material and for the propagating medium. This result is indicated by the theory.

(4) With a weak reflector like paraffin harmonics, if they are present and of sufficient magnitude, have a very marked effect.

(5) The values of the velocity of sound in the different materials used as determined by the method outlined here are greater than values determined by static and low frequency methods. As explained above this is due to the fact that Young's modulus of elasticity does not apply. The bulk modulus, as used for an infinite body, is more nearly applicable.

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THE GEOLOGY OF CEYLON[1]

By Frank Dawson Adams[2]

Abstract

The Island of Ceylon is composed almost entirely of crystalline rocks of Archean or pre-Cambrian age. In the extreme north these are overlain by limestones of Miocene or later age. At one point on the northwest coast a very small area of Jurassic rocks lies on the surface of the coastal plain.

The ancient crystalline rocks resemble in many respects the Grenville series of the Canadian Shield. They are largely biotite gneisses, interstratified with which are at least two great beds of white crystalline limestone, often dolomitic, with associated beds of quartzite and of sillimanite-bearing rocks of undoubted sedimentary origin. Charnockite and allied rocks are present also in large amount, especially in the higher parts of the island. The petrography of these rocks is described, and is illustrated by a series of chemical analyses, the first that have been made of the rocks of this island. In structure Ceylon is a portion of a great syncline, deeply eroded, closed on the south, open to the north, where it plunges beneath the Miocene cover.

Three distinct plains of denudation can be clearly recognized in Ceylon. The coastal plain, about 100 ft. above sea-level, a second plain at about 1,600 ft., and a third at 6,000 ft. above sea-level.

The paper presents the first account which has been given of the geological structure of the island, and the accompanying geological map of the island is the first which has been prepared.

Introduction

Marco Polo, who probably had seen more of the world than any other traveller of his time, in his renowned "Book" devotes a short chapter to Ceylon, which begins as follows: "I want you to understand that the Island of Ceylon is for its size the finest island in the world." (54). This opinion expressed in the fourteenth century, notwithstanding all the increase of geographical knowledge, may be reiterated with equal truth in the twentieth century.

Lanka is the name which the Island always bore in song and story both in India and in Ceylon itself. After it had been colonized by Indian settlers it became known to foreigners as Serendib. It was also called Sinhala, whence came the later forms of Ceillam, Ceylan and finally Ceylon. The Greeks referred to the Island as Taprobane, by which name it is mentioned by Milton in "Paradise Lost".

It is probable that early man came to Ceylon from India by means of a then existing land bridge (62). He had not at that time reached the Palæolithic stage of culture, but he attained this later on the Island. Still later came Neolithic men, but whether these were descendants of the Palæolithic men whose weapons are found abundantly in the Pleistocene Deposits of Ceylon or whether they are of another race is unknown. Later still, according to Wayland, came the Veddas and the Naga people from southern India.

While the Mahawemsa—the native Chronicle of Ceylon—carries the history of the Island back to a more remote period than that for which there are any written records of the adjacent Empire of India, the earlier portion of this

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Chronicle is evidently more or less mythical, while little or nothing is known of the history of the Island in remote antiquity. The earliest inhabitants referred to in the Mahawemsa were apparently a people called the Yakkas, who are supposed to be represented by the Veddas, a few of whom still survive as hunters in the dense jungle of certain remote parts of the interior.

It is recorded that these people were in possession of the Island when some Aryan invaders from northern India descended on its coast. These new settlers with an admixture of Veddas and of some more recent accessions from southern India came to be known later as the Singhalese, who in the course of time attained a high civilization, built the great cities of Anuradhapura, Polonnaruwa and Sigiriya in the central part of the Island and constructed one of the finest and most elaborate systems of irrigation of which there is any record in history. By means of this they collected and stored the heavy rainfall of the higher central parts of the Island and distributed it as required over the lower and dryer lands of northern Ceylon, which at that time yielded enormous crops of rice and supported a very large population.

Then came, in successive waves of invasion, the Tamils from southern India, at intervals during the long period from the second century B.C. until 1001 A.D., in which year they looted and demolished the city of Anuradhapura. These invaders also destroyed the great irrigation system of the Singhalese and forced these people to abandon their great cities in the north and retire into southern Ceylon where they established their Capital at a number of places in succession, finally selecting one on the site of which the city of Colombo now stands.

The dense tropical jungle slowly advanced over all that part of the Island where stood these ancient and renowned cities with their palaces and their teeming population, as well as over the great stretches of rich agricultural land which supported them. It buried within its recesses all the remains of a civilization which existed there over 2,000 years ago.

In A.D. 1507 the Portuguese, who were the first people from Europe to reach the Island, settled on the west and south coasts.

In A.D. 1656 the Dutch dispossessed the Portuguese, while in 1796 the country passed into the hands of the British who in that year took possession of the maritime provinces, and in A.D. 1815 occupied the interior of the Island as well.

"The unification of the people of Ceylon under one common allegiance thus effected, the security to life and property under the British flag, the absence of warfare, the development of means of communication and the growth of the planting industry, the gradual extension of the blessings of education especially through the agency of Christian missionary bodies, and above all the growing disregard of the restriction of caste, wrought a complete change in the body politic, and changed the outlook on life of the inhabitants of the country. It is now one of the most thriving colonies of Great Britain developing in democratic and political institutions, copied from the United Kingdom, bidding fair one day to take its place among the self-governing dominions of the British Empire" (14).

View of the coast of Ceylon near Colombo. (*Plate Ltd., Colombo*)

The population is now about 4.5 millions. The Island has prospered greatly since the British occupation. The old irrigation works have been partially restored at an enormous cost, excellent roads have been constructed everywhere throughout the Island, the ancient buried cities to which reference has been made have been recovered from the jungle and partially restored, railways have been built and Colombo is now one of the great seaports of the world.

Tea, rubber and cocoanut plantations yield the chief exports of Ceylon, and the magnificent scenery of the Island attracts visitors from all parts of the world.

Ceylon affords an excellent field for geological study, not only on account of the intrinsic interest of the problems which it presents but owing to the great ease with which these studies may be prosecuted. There is an excellent topographic map of the Island on a scale of one mile to the inch contoured with 100-foot intervals, as well as a series of maps on smaller scales, issued by the office of the Surveyor General in Colombo. Mile posts are placed along all the roads so that it is possible at any point for the observer to determine his exact position. There are furthermore excellent motor roads through almost every part of the Island, with Government Rest Houses so placed that one or other of them can easily be reached every evening.

During a visit to the Far East in 1924 the writer spent the month of November in Ceylon and returned for a brief stay in March of the following year. A third visit to the Island was made in 1927 and seven weeks were spent there in the early part of that year.

In gathering the field data for the present paper nearly 2,000 miles of geological sections on the roads were examined.

The rocks are generally well exposed. The lateritic clay, which results from the alteration of the various rocks under the influence of the tropical agencies of decay, while it mantles and completely hides the underlying rock on the lower levels in certain parts of the Island, is on the higher lands washed off the steep slopes by the heavy rainfall, laying bare great surfaces of fresh rock in many places, and even where the lateritic mantle is continuous, good exposures are obtained in the small quarries which the Public Works Department has opened up for road metal every few miles along the roads in every part of the Island. The rocks when thus exposed are perfectly fresh in almost all cases, thus affording excellent material for the petrographer.

Ceylon still presents a wide field for further study. In the following section a brief résumé is given of the contents of the more important publications which have appeared, dealing with the geology of the Island.

The present paper is an attempt to correlate all the information on this subject which has appeared in print up to the present time, adding to this the results of the author's own studies. It presents the first geological map of the Island which has been prepared, as well as the first attempt to work out the geological structure of the Island as a whole. It also contains the first study of the chemical composition of the rocks of Ceylon, the only chemical analyses of rocks from the Island which have hitherto been made being one complete

and one partial analysis of corundum syenite by W. C. Hancock (27) and four partial analyses of limestones which latter are given below, in the chapter dealing with these rocks.

In the present paper 21 new and complete chemical analyses of the more important rock types of rocks of Ceylon are given.

Previous Work and Literature

A "Bibliography of Ceylon Geology" which was prepared by A. K. Coomaraswamy in 1906 (20) comprises one hundred and eighteen titles, and since that year a few additional papers have appeared. A study of this literature however shows that the great majority of these books and papers contain but very few important contributions to the geology of Ceylon. The majority of them deal with mineralogy and contain descriptions of, or brief references to, specimens of gems collected in Ceylon and sent to Europe for examination. Others are narratives of travel in which appear short references —generally of but little value—to the mineralogy or geology of the Island. The following are the more important of these papers which deal with the geology of Ceylon, in the order of their appearance.

John Davy, M.D. Modder says that "the first real attempt to describe the geology of the Island" was made by John Davy, M.D., a brother of Sir Humphrey Davy. He wrote however between 1818 to 1823 at a time when the science of geology was in its infancy and his contributions are of little value (36, 37). He speaks of the narrow valleys filled with detritus and states that no natural lakes are found in the Island. The two principal kinds of rocks exposed are gneiss and dolomite. He refers also to an "interrupted chain" of recent sandstones which surrounds the Island in horizontal beds lying between high and low water mark, but not extending inland beyond the beach. He also mentions that the native matrix of sapphire, ruby cat's eye and zircon is gneiss, a statement which has not been substantiated by later investigation except in the case of the mineral zircon (38).

Richthofen, Fr. (55), spent ten days in Ceylon in the year 1860 and from there wrote a short letter to the Geological Society of Germany. He states that the Island is composed chiefly of gneiss and that this rock in Ceylon is very remarkable in character in that granular calcite is almost invariably present among its constituents—a statement which again is quite incorrect.

Lacroix, A. (43), in the paper referred to below gives the earliest published descriptions of the microscopical characters of rocks from Ceylon. He did not visit the Island but described certain specimens collected in Ceylon by Leschenault de la Tour in 1819 and which are now preserved in the collections of the College de France in Paris. These came from the districts about and between the cities of Colombo and Kandy. Only a few rocks from Ceylon are described, the paper dealing chiefly with rocks collected in India and elsewhere.

Melzi, S. C. G. (48), describes certain rocks which he collected between Colombo and Kandy as well as others from the higher portions of the Island and from the shore about Batticaloa and Hambantota. These rocks he

arranges under the four classes of dioritic gneiss, pyroxene granulite, garnetiferous pyroxenite, and granular acid gneiss, but states that these several classes pass into one another. According to his observations the more elevated portion of the "Altipiano" of Ceylon is composed exclusively of pyroxene granulite traversed by veins and masses of intrusive granite. He gives very few references to precise localities.

Modder, F. H. (50) "This province forms part of a plain which surrounds the mountain district and is like a sea of rolling gneiss with waves on the strike north and south". The dip is generally nearly vertical. The exposures have rounded outlines due to the action of the atmosphere and to a concentric lamination which they possess. The plain ends in a white sandy beach. Dolomite overlies the gneiss in various parts of the province, a number of localities where this rock is found are mentioned. He says the land has been slowly rising from the sea. In a second paper Modder (51) describes certain curious imitative forms assumed by hills of gneiss in the vicinity of Kurunegala and refers to Singhalese legends which account for their origin.

Diersche, Max (39). In the winter of 1894 Professor Ferdinand Zirkel made a short stay in Ceylon and collected a number of specimens from various parts of the Island, which upon his return he handed to Dr. Diersche who examined them petrographically. In this paper Diersche describes certain of these rocks and then gives an account of the graphite deposits at Ragedara, the largest of the occurrences of the mineral in Ceylon, and of certain inclusions of other minerals in the graphite there. Although he deals with but few rocks, his descriptions are very detailed and his contribution to the petrography of Ceylon is one of the most important which has yet been made. Diersche arranges the rocks which he describes in the following classes: gneiss, which he says is the most widespread rock on the Island, normal and pyroxene granulites, granite, limestone, quartzite and sea sand. He states that the granulites of Ceylon differ from those of the original area of typical granulites in Saxony in that the acid and basic granulites are less intimately associated with one another, occur in larger independent bodies, are coarser in grain and more massive in structure. He found in the pyroxene granulites of Ceylon two rhombic pyroxenes—namely, enstatite and hypersthene and two monoclinic pyroxenes, a non-pleochroic sahlite and a pleochroic diallage-like variety. Diersche labored under the disadvantage of not having seen in place the rocks which he describes. Dealing merely with hand specimens he had no opportunity of observing the relation of the various rocks to one another or their structure in the field.

Parkinson, John (52) made a short visit to Ceylon in 1900 and has described the mode of occurrence and petrographical character of certain "granulites" and limestones occurring in the south-central portion of the Island.

Weinschenk, E. (69). Like Diersche he compares the Ceylon occurrences with those of the Granulite Region of Saxony, stating that they are similar in composition but differ from these both in external appearance and in their

microscopic structure, as well as in the fact that the several varieties form independent masses instead of showing the intimate association with one another which they display in the Saxon area.

Coomaraswamy, A. K. and the Administration Reports. The largest body of important data on the geology of Ceylon is contained in the "Administration Reports—Mineralogical Survey—Ceylon", issued by the Government annually from 1903 till 1909. This Survey was established toward the close of 1902 with A. K. Coomaraswamy, B.Sc., F.G.S., as Director, and James Parsons, B.Sc., F.G.S., as Assistant Director. In 1907, Mr. Coomaraswamy retired and was succeeded in the Directorship by Mr. Parsons with J. A. Daniels, B.A., as Assistant Mineral Surveyor. In 1908 and 1909—Mr. Parsons having died—Mr. Daniels acted as Director. These Reports were not issued after 1909. Each Report consists of twenty pages or less, made up chiefly of short descriptions of various mineral deposits which promised to be of economic value, but there are also recorded many valuable observations on the rocks of various parts of the Island.

At the present time the position of Principal Mineral Surveyor is held by J. S. Coates, B.A., but the time of this officer is unfortunately largely occupied in administrative and statistical work. A paper entitled "The Mineralogy of Ceylon", having essentially the same scope as that on the "Crystalline Rocks of Ceylon" by Coomaraswamy (see below) was read in November, 1925 by Coates before the Geographical Society of Ceylon, and was published in the Colombo daily press.

In these Administration Reports, Coomaraswamy has given the fullest and most accurate accounts which have appeared of the geology of the ancient crystalline rocks of Ceylon, and most of this information is also to be found distributed through certain papers by him in other publications—among these the most important are those to which references are given in this paper (24 to 30). Coomaraswamy having visited all parts of Ceylon had a much wider acquaintance with rocks of the Island than any of his predecessors. He states that the term gneiss used in the sense of a rock having a "gneissic structure" is applicable to most of the rocks of the Island. If the term "granulite" is used, as it is by many writers to designate a gneiss containing garnet, a large proportion of the crystalline rocks of the Island might also be termed granulites. He also mentions that the crystalline rocks of Ceylon belong, in large part at least, to the "Charnockite Series" which Holland described in southern India. Most of these crystalline rocks he believed to be of plutonic igneous origin, their more or less well marked foliation, a character which he recognized is almost universally present, is not due to pressure after the solidification of the rock but to movement prior to its consolidation. He thinks that metamorphosed sediments, if present at all, are rare.

He divides the crystalline rocks of Ceylon into the following classes—(i) Granular quartz rock, which he regards as an extremely acid type of granulite; (ii) Leptynite; (iii) Charnockites ranging in composition from acid hypersthene granites to basic norites; (iv) Zircon syenites (Balangoda Group),

pegmatites, etc.; (v) Crystalline limestones—with the wallastonite-scapolite rocks of the Galle Group. He says that the crystalline rocks have been thrown in a series of N.N.W.-S.S.E. folds due to the "Taprobanian" movements, and refers to the topography as influenced by the prevailing strike or by the jointing of the rocks. He has contributed also many valuable papers on the mineralogy of Ceylon.

Wayland, E. J. (62, 65) who was connected with the Mineralogical Survey of Ceylon, as Assistant Mineral Surveyor from 1914 to 1916, published two important papers, in the first of which he deals with the geology of the coastal plain, the relation of its positive and negative movements and the occupation of the Island by palæolithic and neolithic man. He also mentions the existence of a second and higher "periplane". In the second paper he describes the occurrence near Tabbowa, on the shore of northwestern Ceylon, of a small but very interesting occurrence of shallow-water non-marine beds holding fossils of Jurassic age.

Somerville, Commander Boyle T., R.N. (60). Describes and gives maps of the submerged plateau which surrounds the Island and extends outward to an average distance of twelve miles from its shore, merging into that surrounding the southeastern coast of India. The paper also discusses the origin of certain coastal forms.

Adams, Frank D. (1). This and certain other papers dealing with minerals of economic importance which occur in the Island are referred to in the section dealing especially with these minerals.

Adams, Frank D. (2). This is an abstract of the present paper.

Topography

The Three Peneplains

The Submarine Plateau around the Island

Epeirogenic Movements in Ceylon

The Strike of the foliation of the Crystalline Rocks as influencing the topography of the Country

The Red Lateritic Clay

The Rainfall and the Rivers

The Three Peneplains

The Island of Ceylon is oval in shape and is offset a little to the east from the most southerly point of the peninsula of India. It has an area of 25,332 square miles, being therefore about one-half the size of England and is 270 miles long and 140 miles wide at its greatest breadth.

It is bordered by a low coastal plain which is very narrow along the southern margin of the Island but widens out on the western and becomes still wider on the eastern side, while to the north it expands into the great plain which forms the whole northern half of the Island.

This plain is incised in rocks of Archean age but on its surface there are found in places alluvium and raised beaches of recent age, as well as some thin deposits probably laid down upon it in the Pleistocene.

In the Jaffna peninsula and the adjacent part of the extreme northern end of the Island the Archean rocks of this plain are covered by Miocene limestones, and at Tabbowa there is an isolated occurrence of Jurassic age. Sea cliffs are absent or are very unusual.

In the interior of the southern and central portions of the Island, these Archean rocks rise into a "massif" forming a high rugged country which presents a striking contrast to the surrounding coastal plain and which culminates in a series of peaks of which the best known, although not the highest, is Adam's Peak, seen far out to sea on approaching the Island from the west. This central "massif" occupies about three-fifths of the area of the Island.

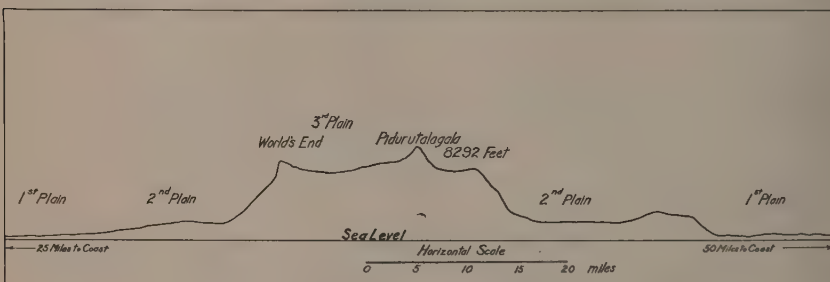


FIG. 1. *Section across the central part of Ceylon.*

On the slopes of this central "massif" two other peneplains are incised at higher levels (see Fig. 1). There are thus three well-marked plains of erosion cut in the rocky framework of the Island. These with their respective elevation above sea level are as follows:

Third Peneplain	6,000 ft. above sea level.
Second Peneplain	1,600 ft. above sea level.
First Peneplain—the Coastal Plain	100 ft. above sea level.

A typical area of the First Peneplain (the Coastal Plain) is shown in Plate II. This is a reduction from Map Sheet J.12 of the Topographical Survey of Ceylon, the area represented being in the Batticaloa District in the southeastern portion of the Island.

Another part of this First Peneplain with the escarpment between it and the Second Peneplain, as well as a typical area of the latter, is shown in Plate III, which is reduced from Map Sheet M. 21 of the same Survey in the Kongala District of southern Ceylon.

Plate IV is a photograph of the surface of this Second Peneplain, also in southern Ceylon.

Plate V represents a view over the Third Peneplain as seen at Nuwara Eliya, the well-known summer resort of Ceylon, 6,200 ft. above sea level.

Topographic map (Sheet J. 12) of the Ceylon Survey in the Batticaloa District of Southeastern Ceylon, showing surface of the Coastal Plain with erosion remnants. Scale 2½ miles to 1 inch.

Topographic map (Sheet M. 21) of the Ceylon Survey in the Kongala District of Southern Ceylon showing the eroded surface of the Second Peneplain (to the N.W.) and that of the Coastal Plain (to the S.E.) with the escarpment bounding the former.—Scale 2½ miles to 1 inch.

Land being cleared for planting rubber trees—Ceylon. The photograph presents a typical view over the Second Peneplain. The surface is strewn with boulders of decomposition. (Plate Ltd., Colombo)

PLATE V

General view of Nuwara Eliya from the Ramboda Road. The photograph presents a view over the Third Peneplain with Monadnocks (in the distance) rising from it.—(Plate Ltd., Colombo).

Each of these peneplains rises somewhat on going inland toward the foot of the next higher plain. Thus the coastal plain rises to about 300 ft. around the foot of the abrupt ascent to the second peneplain. The second, in some places near the escarpment of the third peneplain, rises to approximately 1,900 ft. The highest, while well marked, is somewhat more uneven than the others.

From the surface of each of these peneplains there rise erosion remnants in the form of ridges, often cut up into clusters of hills or worn away to isolated buttes sometimes with sides so abrupt that their summits are almost inaccessible. The two higher and older plains furthermore have been in places deeply incised by the agencies of weathering and erosion since their elevation above base level. A large isolated and deeply dissected remnant of the third or highest peneplain is seen in some high broken country lying to the east and southeast of Badulla.

From the surface of the highest plain rise the great peaks which crown the Island, among which may be mentioned Pidurutalagala—8,292 ft., Kirigalpotta—7,857 ft., Kolapatanahala—7,754 ft., Totapola—7,741 ft., and Adam's Peak—7,360 ft. in height.

On the third or highest peneplain are two large depressed and more or less circular areas of approximately level ground. The larger is bounded by a ridge on which are situated Adam's Peak, Kirigalpotta, the Horton Plains, Totapola, Hakgala, Nuwara Eliya, and Great Western. This boundary is less well defined on the northwest margin, but Laxaplana and Aberdeen Falls are just below the margin here. The northwest strike of the rocks underlying this plain is marked by an interrupted ridge which runs across the plain in the above direction, having Kirigalpotta Mountain at its southeast end. Parallel to the ridge there is, on the southwest side, a deep valley with two others, less well marked, one on either side, all three lying to the southwest of the ridge and parallel to one another. The stream in the central valley displays an abundance of falls, that in the valley to the southwest of it has the beautiful Laxaplana Falls. The stream in the most northeasterly valley apparently has no falls but descends to the lower level by a series of cascades. The northwest and southeast strike of the country rock is thus traceable across the south half of this great circular area. The apparently structureless character of the northeasterly half of this circular area, which is without ridges, may be due to the rocks flooring it being horizontal in attitude.

The second depressed area is also nearly circular but is less accentuated in character. Welimado lies in its centre, Wilson's bungalow and Manawella falls on its edge. Banderawella lies within it. On the south it is bordered by the cliff at Haputale, and on the east it has no mountain rim. It is somewhat lower in level than the other area.

Pidurutalagala, which is the highest point on the Island, lies near Nuwara Eliya, rising from the third peneplain between the two depressed areas above mentioned.

A photograph of a portion of the surface of this second depression with the third peneplain silhouetted on the sky-line in the distance, is shown in Plate VII(a).

One of the finest and most extended views of these three plains is that seen from Haputale, a station on the Ceylon Railway situated on the edge of one of the above mentioned circular depressions in the highest peneplain at a height of 4,731 ft. above the sea in southeastern Ceylon. From here looking to the west and southwest all three plateaus can be clearly seen rising one above the other in the great escarpment which here bounds the central "massif". The top of the escarpment is formed by the third peneplain. Lower down the second plain can be seen notched into the face of the escarpment. On it can be seen distinctly the village of Kuragalla, while at the foot of the precipitous rock face between the second and the lowest plateau is the village of Dadamaula.

Looking off to the southeast there is an uninterrupted view across the lowest plain to the ocean which may be descried on the far horizon on clear days.

Each plateau shows plainly the erosion remnants upon its surface. Those on the highest plain are seen in outline against the sky. Those on the second plateau can be recognized from their form and direction as strike ridges dipping to the west at angles of 30° or 40°.

The descent from the second peneplain to the lowest or coastal plain is almost a precipice, and looking out from Haputale over this lowest plain a most remarkable panorama of vast and widespread destruction meets the eye, for rising from its surface as far as the eye can reach, out to the margin of the ocean, can be seen a vast number of ridges, hills and buttes, remnants of the higher land which have as yet survived the action of the forces which have reduced the rest of the plain to a base level.

In the belt of country near the escarpment these are larger, higher and more numerous having the form of ridges rather than isolated hills, their summits frequently rising to the level of the second plain. Further out they become lower and more scattered and along the sea coast are seen only at wide intervals and are seldom more than a few hundred feet in height. Here and there, however, far out on the practically level plain rise great fortress-like masses whose summits are coincident with the level of the second plain. One of the most striking of these, known as Westminster Abbey, is situated 20 miles from the east coast of the Island, north of the road to Pottuvil. Another great mass to the south of the same road but further west, near Monaragala, rises abruptly to a height of 3,600 ft., which is above the level of the second plain, being either a remnant of the higher land which escaped the base levelling which developed the second peneplain, or which may possibly owe its elevation to faulting. The course of these ridges and the alignment of the smaller hills follows closely the strike of the gneisses of which they are composed.

The streams crossing the coastal plain in some cases cut directly through and across these ridges, having been flowing in their present course over the surface of the country before the present peneplain had been developed and while these ridges still formed part of the higher plateaus. Wayland (62) cites two instances of this, namely, that of the Kelani-ganga above Hadduwa which cuts through a high rocky ridge separating the end of it from the main mass, and the Kalu-ganga which flows across the range between Nambapana and Dumbara.

Near Kurunegala, on the eastern margin of the "massif", 58 miles northeast of Colombo, are the well-known "Animal Rocks", a long ridge of gneiss rising to heights of from 300 to 700 ft. above the general level of the plain and weathered out into forms which, from their fancied resemblance to those of certain animals, are known as "Elephant Rock", "Tortoise Rock", "Goat Rock", "Crocodile Rock", "She-Elephant Rock", "Eel Rock", "Lump of Salt" and "Tat of Leaves". Near them is the "Wanduruwewa Tank", a large artificial lake which is one of the numerous remnants of the great irrigation system constructed by the Singhalese in ancient times, and to which reference has already been made.

A quaint and characteristic Singhalese legend accounts for the origin of these rocks as follows: During a severe drought which visited this district long ages ago the animals after whom the rocks are named came out of the jungle in search of water. An aged Singhalese woman who was in the field when the animals approached, fearing that these intruders might exhaust the water in the tank, on which the lives of the people of the town depended, should they see it and endeavour to slake their thirst by drinking from it, placed a large lump of salt on the ground in front of the elephant, who was heading the band of marauders. The elephant began licking this proferred dainty, which gave the woman time both to construct a rude "tat" or screen of leaves which hid the tank from the monster's view, and to pray to the gods to avert the impending calamity. Before the lump of salt had been seriously reduced in size the gods answered the woman's prayers and the animals were turned to stone, as were also the lump of salt and the "tat" of leaves, all of which can now in their petrified condition be plainly seen (51).

Two other striking remnants of erosion and decay are the hill of Sigiriya and the hill at Dambulla—both rising abruptly from the coastal plain on the northern border of the Archean nucleus, about ten miles from one another. Both are renowned sites in the history of Ceylon. Sigiriya is a post-like body of gneiss, somewhat oval in section, whose level summit is 600 ft. above the level of the surrounding jungle-covered plain. This summit is entirely inaccessible without the help of ladders, since the rock at its top overhangs around the whole periphery. It was the rock fortress to which King Kasyapa retired to avoid his brother's vengeance after obtaining the throne by the murder of his father, Dhatu Sena, about 500 A.D., and here he reigned for eighteen years. The populous city which at that time lay around the base of the fortress has now entirely disappeared and the great jungle of central Ceylon occupies its site. Looking out from the top of Sigiriya far and wide on every side the great expanse of the level jungle with its deep green foliage extends like a sea. Rising abruptly from it at intervals are hills, some with rather smoothly rounded outlines, some with flat summits, others showing abrupt cliffs or scarps rising to a peak.

In the side of the hill at Dambulla is excavated the renowned rock temple which bears this name.

The breaking down of the second peneplain to the level of the lowest one is also excellently seen on the western side of Ceylon by the traveller going down from Kandy to Colombo on the Ceylon Railway.

Kandy itself lies in a depression on the second plain. Looking to the south as the train passes between Peradeniya and Alagalla the deep dissection of this second plain is seen by great valleys running into its margin, the summits of the intervening remnants of the plain showing a general accordance of level. Many of these take on curious and bizarre shapes—some flat-topped, others presenting sharp pinnacles and wedge-shaped forms. As the train winds its way down to the lower plain, from time to time glimpses are obtained of the bottoms of deep valleys where little villages nestle among the paddy fields amid this scene of terrific destruction, and the block-strewn slopes when not too steep to support vegetation are covered with palms, Bread fruit and Jack fruit trees, papoys or other forms of tropical vegetation forming a mantle of vivid green through which the bare ribs of the ancient gneisses thrust themselves upward at frequent intervals. By the time Rambukkana is reached these rocky ridges have disappeared and the railroad passes out on to the almost level surface of the coastal plain.

The Submarine Plateau around the Island

In connection with the existence of the elevated plateaus or peneplains to which reference has been made, the results of a study of the submerged portion of the island beyond the immediate coast line made by Commander Boyle T. Somerville, R.N., are of interest and importance (60). Commander Somerville shows that the Island is surrounded by a submerged plateau which extends to an average distance of twelve miles from the land. The average depth of the water on this plateau is about 36 fathoms or 216 ft. Its outer margin is well marked, beyond it the sea bottom sinks rapidly to a depth of 3,400 ft. a distance of two miles from the margin and to 6,000 ft. at a distance of ten miles farther out.

To the north of Ceylon this plateau merges into that which surrounds the coast of India. This continental shelf, where it borders India, is everywhere wider than it is about Ceylon, except possibly along a portion of the coast of Madras. Writing of this, Wadia (61) says, "The whole seaboard of India is surrounded by a submarine ledge or platform the 'plain of marine denudation' where the sea is very shallow, the soundings being much less than 100 fathoms." Recognizing this shelf as a submerged portion of the continent of which both India and Ceylon form part, it will be noted that this Asiatic peninsula at its extremity turns off sharply in an easterly direction in the same manner as South America does before it sinks abruptly into the ocean depths.

Somerville states that the outer edge of this plateau follows the general trend of the coast line, but off the eastern side of Ceylon there are in it several deep and narrow notches or indentations, the two most notable of which are those off Trincomalee (Koddiyar Bay) and off a point five miles north of Batticaloa, respectively, where the end of the deep water approaches to less than a mile of

the shore in the first instance and within two miles in the other. In that part of the coast which he had surveyed up to the time of the publication of his paper, he states that but one other notch occurs in the continental shelf—namely, that off Panadure, where the 100 fathom line approaches the coast to within a distance of about nine miles. It is worthy of note, in connection with the question of the origin of these indentations in the submarine platform, that one of the largest rivers in Ceylon, the Mahaweli Ganga, comes to the coast at Trincomalee, while two streams, the Magalowatavan Oya and the Mundeni Aru, enter the lake which opens out to the sea at Batticaloa.

Commander Somerville also notes the absence of coral reefs around the coast of southern Ceylon, with the exception of little patches here and there as at Hikkaduwa and Galle, but no fringing or barrier reef, and that scarcely any specimens of coral are brought up by the lead on sounding. The brown color of the sand forming the beach round the southern shores would alone point to the absence of coral, being so dissimilar to the glaring whiteness of the beaches behind coral reefs. He mentions, however, that near the railway line in the vicinity of Ambalangoda the natives dig coral out of an old reef which is now about half a mile from the coast, and which is here covered by four or five feet of black humus. His explanation of this is that the coast is in process of extending outwards so rapidly that the growth of reefs is prevented by their being smothered by soil washed out from the land.

Epeirogenic Movements in Ceylon

It is not proposed here to discuss the question as to whether the three peneplains above sea level and the fourth peneplain represented by the submarine plateau, to which reference has just been made, were produced by marine erosion or by the processes of subaerial denudation. Wayland believes that the first and second peneplains are plains of marine denudation. Wadia and Medicott and Blanford (61) assign the submarine plateau (about India) to the same agency. The writer, while not in possession of any conclusive evidence on the question, is inclined to favor the view that they are all plains of subaerial denudation. Coomaraswamy (19) has expressed the same opinion in the case of the coastal plain. It makes, however, but little difference in interpreting the significance of these phenomena which view proves eventually to be correct, for whether a plain was worn down to its base level, the sea level, by the atmospheric forces or whether it was incised by the action of the waves a little below sea level, the surface of the plain in each case practically represents the level of the sea at the time when it was developed.

It has frequently been stated that the Island of Ceylon has never been under water since the very earliest times in geological history. This statement has been based on the belief that no rocks of sedimentary origin were to be found on the Island except immediately along the sea coast. A closer study of Ceylon, however, shows that it was entirely submerged in pre-Cambrian times since sediments of this age, now highly metamorphosed, are found widely distributed over the higher, and probably occur on the highest, parts of the

Island. Since then it has always been in large part under water but throughout the long geological ages, it has been a "positive" element in the earth's crust having, with some minor oscillations, been rising out of the sea in successive stages of uplift. While the processes of tropical denudation have been continuously wasting the Island away, the process of epeirogenic uplift has renewed it from age to age.

The following stages of this uplift can be traced:

1. The Island rose out of the sea to a certain height and remained stationary for a prolonged period during which what is now the Third Peneplain was incised.
2. The Island then rose another 4,400 ft. and remained at this level for long ages, during which the Second Peneplain was cut.
3. A third elevation then took place amounting to 1,500 ft. and the Island remained at this level until the greater part of it was worn down to the level of the First Peneplain—the present Coastal Plain.
4. Finally it was again elevated until the present Submarine Plateau was at or above the level of the sea.

This "positive" or rising movement, however, was interrupted during its course by certain minor "negative" movements or subsidences. Thus between 3 and 4 there was a negative movement which carried the first peneplain some hundreds of feet below sea level, and upon it were deposited the Miocene limestones. A second negative movement took place still later when the waters of the present ocean passed over the submarine plateau (number 4) covering it to a depth of some 216 ft.

It may be noted that this submarine plateau is not only continued around the coast of India but is found about the coast of Malaya where it is 300 ft. below sea level, about the coast of the stable western half of the Netherlands East Indies where its depth is stated to be approximately 240 ft. (11), while about the coast of New South Wales there was a submergence of a little over 200 ft. (34).

In recent times there have been in Ceylon a number of minor oscillations of coast level amounting to a few feet in extent (35), and there is reason to believe that a gradual rising of the coast is now in progress (63).

When these successive elevations took place in geological time is not known as yet. It is doubtful whether this can be determined from the study of Ceylon itself. If the three higher peneplains can be traced over into southern India, where there are sedimentary deposits whose age can be recognized, it may be possible to determine the epochs at which these remarkable epeirogenic movements took place. It is, however, certain that the present coastal plain had already been incised in Miocene times. The calcareous material at the base of the Miocene strata can be seen to fill cracks and fissures in the gneisses of this plain, which cracks and fissures must have already been in existence when the plain passed beneath the waters of the Miocene sea. Further data concerning the age of this peneplain can probably be obtained from a close study of

the small area of Jurassic rocks at Tabbowa. Wayland states that these lie on the plain, are shallow water deposits and are faulted into the plain. Whether they were base-leveled with the rest of the plain or not, is a question which if answered would have an important bearing on the problem of the age of the peneplain itself.

The higher peneplains date back to much earlier periods in the history of the earth.

The existence of these peneplains with the Monadnocks rising from the level of the highest one, brings up the question of the amount of denudation which the Island has undergone.

As the top of Pidurutalagala, the highest point in Ceylon, is 8,292 ft. above sea-level, and the submerged plateau is 216 ft. below it, at least 8,508 ft. must have been worn off the original surface of the land, and as the highest rock is charnockite, which is believed to be a plutonic igneous rock, the original surface must have been considerably higher than the present top of the highest peak. How much higher cannot be determined but it is safe to say that not less than about 10,000 ft. of hard crystalline rock has been removed by denudation from the peripheral portion of the Island.

Whether these three upper peneplains incised in that portion of Ceylon which stands above sea level at the present time can be recognized in southern India is not known. Wadia, however, states in his "Geology of India", in the chapter on Physical Features, that "the greater part of the Peninsula is constituted by the Deccan Plateau. This is a central tableland, extending from 12° to 21° North Latitude, rising about 2,000 ft. mean elevation above the sea, and enclosed on all sides by hill-ranges. To its west are the Sahyadris, or Western Ghats, which extend unbroken to the extreme south of Malabar, where they merge into the uplands of the Nilgiris, some of whose peaks rise to the altitude of 8,700 ft. above the sea-level (Dodabetta peak), the highest point of the Peninsula."

It may be that this Deccan Plateau represents a continuation of the second peneplain of Ceylon. If so, the third or highest peneplain of Ceylon might be found in the uplands of the Nilgiris, whose highest peaks have approximately the same elevation as the highest point of the Island.

A search for these peneplains in Madagascar and other fragments of Gondwana Land, of which Ceylon and southern India formed parts, would be of great interest. If this well defined series of peneplains so clearly seen in Ceylon and which represent what must be very marked physiographic epochs in the history of Gondwana Land can be recognized in the fragments of that disrupted continent, correlations of the greatest value might be made, and very important information secured with reference to the foundering of that great area of ancient land.

The Strike of the Foliation of the Crystalline Rocks as influencing the Topography of the Country

The erosion remnants rising from the three plains just described are, as has been already mentioned, chiefly strike ridges, eventually breaking down into isolated buttes or hills. Their course is always aligned on the strike of the rock out of which they are cut, they sweep around the island following, with the strike, approximately the curves of the coast line[1]. In the office of the Surveyor General in Colombo there is an admirable relief map of the Island based on the one inch contoured topographical map of Ceylon issued by his department. This displays in a remarkable manner the course of these lines of strike ridges, down the west side of the Island in a general north to south direction, then sweeping symmetrically around to the east till they assume an east and west course and then curving back again to the original north and south course as they pass up the east side. These curves present the appearance of a series of garlands pendent from the northern extremity of the Island and so close is the coincidence of the strike ridges with the strike itself, that in the Morawacka district, where the outcrops are so few in number, owing to the almost continuous covering of residual lateritic clay, that it is difficult to follow the course of the strike in the field owing to the scarcity of exposures, the somewhat complicated structure can be clearly traced by examination of the relief map in question.

These strike ridges under the influence of secular weathering generally present a dip slope and a mural escarpment. When seen projected in outline against the sky they show a regular serrated appearance quite unlike the irregular notched outline commonly seen in mountain ridges.

This latter topographic form is excellently seen when looking to the north from Galaha, a village situated on the second peneplain at a point seven miles from Kandy in a direction a little east of south. It results from the stripping off of one layer of rock after the other on the dip slope.

The whole ridge gradually weathers, from the surface downward, into a red clay and as this process proceeds great blocks of the still unaltered rock retaining a more or less angular shape remain embedded in this residual clay. As this latter is washed down the slope by the heavy tropical rains, these blocks become exposed upon the surface. What is taking place is not so clearly seen while the surface is covered with jungle but when cleared for the planting of rubber or tea the scene presented is a striking one, the whole surface being littered with these blocks often of enormous dimensions. Small quarries for road metal are sometimes opened up in a single block. The tea bushes and rubber trees are planted in the residual soil between the great blocks, which tend to hold the soil in place on the hill sides and thus slow down the process of denudation (Plate IV). The precipice of the mural escarpment (28), on the other side of the ridge presents a still more striking scene, for here the residual

[1] *This coincidence of the direction of the coast line with the strike of the gneiss which forms the country rock is also seen in southern India on the Coromandel Coast.*

soil is washed away as fast as it is formed and blocks, often of colossal size, fall from the nearly vertical face and pile up at the foot of the precipice, frequently forming a veritable "felsenmeer". The process is shown diagrammatically in Fig. 2. The mural wall is thrown back faster than the dip slope is lowered and thus it gradually recedes across the surface of the country. The whole bed (or series of beds) is in this manner stripped off, lowering the general surface to the extent of its thickness and exposing underlying beds which are in their turn removed by the same process. In this manner the denudation of the country has gone forward throughout the ages.

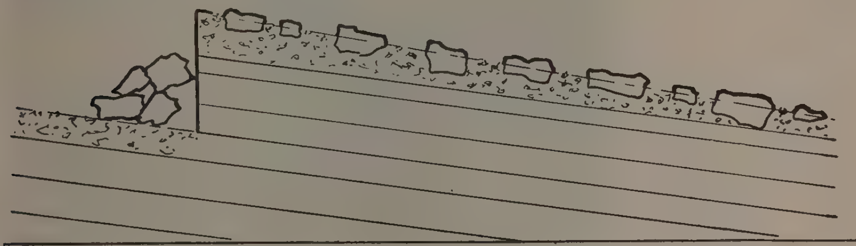


Fig. 2. *Denudation of the high land of southern Ceylon with the development of mural escarpments and dip slopes.*

The Red Lateritic Clays

Where in quarries and road cuttings good sections are exposed from the surface of the laterite through to the fresh underlying bed rock, it is interesting to note the rapid passage from soil to perfectly fresh rock. The underlying rock is usually perfectly fresh to within an inch or two of the lower surface of the laterite clay arising from its decay. Blocks or boulders of decomposition can be seen here and there enclosed in the red clay or laterite and often for a distance of some feet above the surface of the fresh rock the texture of the latter can be seen to survive in the residual clay, probably because the metasomatic processes of decay are not as yet quite complete, while in the upper portion of the clay no survival of this rock texture can be detected.

A photograph of a cutting in gneiss where this rock is decomposing into red lateritic clay, displaying the features just mentioned, is shown in Plate VI.

Another section through lateritic clay is seen in Plate VII (b).

As a result of this weathering under tropical conditions the hills take on a different shape and sharper outlines than in northern countries, where glacial action plays its part, giving to the landscape a different and distinctive character.

The Rainfall and the Rivers

There is an abundant rainfall upon the high lands in the centre of the Island during both the northeast and the southwest Monsoons. On the low lands of the north the rainfall is less, especially on a strip of coast on the northwest side of the side of the Island about Manaar, the moisture-laden winds

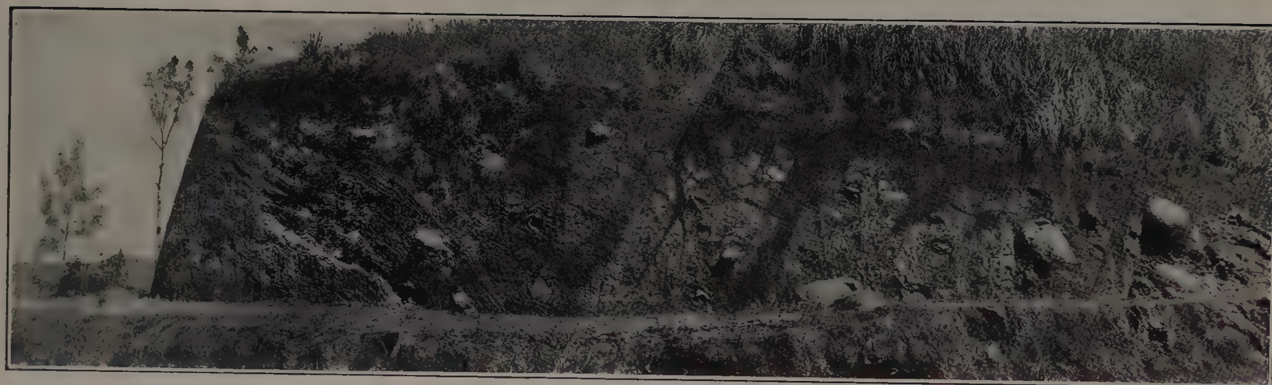
passing over these with less condensation and precipitation. There is, however, except in exceptional seasons, sufficient moisture to cover the land everywhere with verdure and in many parts with dense tropical jungle. This with the striking scenery of the higher lands and the wonderful colors of the sea as it rolls in on the long stretches of low palm-girt shore gives to Ceylon its well deserved reputation as one of the most beautiful islands of the world (see Plate I).

While the low country of northern Ceylon does not now produce as much rice as in the former times when it was irrigated, the high central area is much more productive being covered with tea and rubber plantations, the former at the higher levels and the latter at intermediate heights.

The rain which runs off the surface of the country is carried away by sixteen rivers or streams which for the most part rise in the high lands in the centre of the Island. The longest of these is the Mahaweli Ganga, 206 miles in length, which flows by Kandy, the former Capital, and enters the sea at Trincomalee. The Kelani, 93 miles long, is the next in importance and enters the sea at Colombo. None of these are navigable except for small flat-bottomed boats. These rivers tend to follow the strike of the country rock and they therefore in most cases occupy V-shaped strike valleys. As, however, the strike sweeps around the Island, except on the north where the Archean disappears beneath the Miocene limestones, the rivers must eventually cross it to reach the coast, as, for instance, the Mahaweli Ganga does below Getembe, and in these portions of their courses they frequently run in a series of rapids (28). Coomaraswamy considers that these rivers when crossing the strike are following the course of joint planes (24). He is of the opinion that there are few faults on the Island and that none of them have a throw of more than a few feet.

The red lateritic clay which is washed down from the hill slopes and accumulates in the valleys often for long distances completely conceals the underlying rocks. The swollen streams running through these valleys in times of heavy rain carry their burden of clay out to sea, their waters being bright red in color. On the strips of flat land which border these streams, the fertile alluvium is cultivated and forms the "paddy fields", where the rice which constitutes so large a part of the daily food of the people is grown. Beneath this alluvium, especially in the deep valleys which intersect the country in the districts about Ratnapura, Pelmadulla, Balangoda and other places in southern Ceylon, certain gravels occur in which are found most of the gems for which the Island has been renowned since the dawn of history, and to which further reference is made elsewhere in this paper.

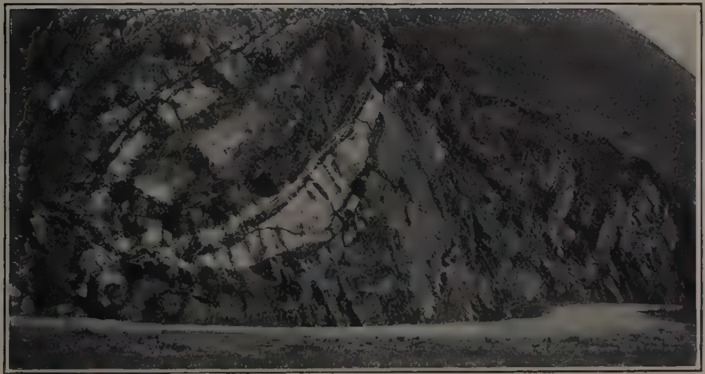
PLATE VI



Gneiss weathering into red lateritic clay—The gneissic structure of the original rock can still be traced in the laterite. The boulders of decomposition are also well seen. Road between Haputale and Bandarawela—mile post 18.5—Southern Ceylon.

(*a*) *The Third Peneplain is seen forming the sky-line in the distance. The lower land in front is one of the depressions in the Third Peneplain. From road between Haputale and Bandarawela—mile post 19—Southern Ceylon.*

(*b*) *Laterite being excavated for road construction. The little pillars are portions of the laterite left to show the height of the original surface. Road between Akuressa and Matara—mile post 3—Southern Ceylon.*



(*c*) *Bands of Quartzite (white) and gneiss folded back upon themselves in the form of a hoop. Ambawela Road near its junction with that from Nuwara Eliya, Southern Ceylon.*

The limestones attain a considerable thickness and are highly fossiliferous. The Areno-argillaceous beds are usually less than 50 ft. thick and unfossiliferous—only at Minihagalkanda do they include thin intercalations of limestone with an abundant fauna. The thickness of the Jaffna limestone is unknown and its base has not been seen. Wayland believes that its thickness is to be reckoned in hundreds of feet. He is also of the opinion that it is possible that the Ceylon Miocene represents a complete cycle of movement and deposition, that is, depression followed by uplift, the two shallow-water phases being represented by the areno-argillaceous beds of no great thickness and the deeper-water phase—probably one of comparatively long duration—by thick deposits of limestone. Concluding the paper Davies gives a full account of the faunas of the Miocene of Ceylon.

Jurassic (65)

The Tabbowa area lies on the Coastal Plain of Ceylon in the northwestern part of the Island, near the port of Puttalam. The Tabbowa beds consist of a group of shallow water non-marine deposits. The basement beds are loosely consolidated argillaceous sandstones and grits. These are succeeded by a series of brown shaly beds with inconstant beds of a somewhat nodular limestone. Intercalated with these strata are beds of nodular sandstones which pass upwards into a series of massive grits and sandstones. Within the sandstones is a thick layer of pipe-clay full of plant impressions. Stratigraphically the beds are in the form of a faulted syncline. Part of the basal beds appear, according to Wayland, to be faulted into the gneisses. He also states that while the time at his disposal did not permit him to measure with accuracy the thickness of the beds, from the information gathered "it would appear improbable that the approximate figure is less than 2,000 ft." A list of the plants collected from the series is given in Wayland's paper which contains all the information on this area which has been published.

Archean

Subdivisions, Succession and Rock Types

The ancient crystalline rocks of the Island are here designated as Archean since there is every reason to believe that they belong to the primitive ages of the earth's history and are certainly a southward extension of the great area of crystalline rocks in southern India to which this name has been given.

As will be seen by glancing through the section entitled "Previous Work and Literature", various names have been given by different writers to some of the principal types of crystalline rocks which are found in the Archean area of Ceylon. This is largely due to the fact that these names have been employed in different senses by different persons and now often lack sharp definition. It will therefore be necessary to define the sense in which such terms are employed in the present paper.

Some writers in describing hand specimens of rocks brought from Ceylon to Europe for study, rocks which they have not themselves seen in the field, have stated that the rocks from Ceylon are often practically massive in texture. As a matter of fact, there is scarcely an exposure of Archean rock on the Island which does not show a foliation or parallelism of constituents sufficiently well defined to enable its strike to be determined. In almost all cases the strike is quite distinct. Thus the rocks about Mihintale and Kurunegala have been referred to as granites, while in the field they are seen to possess a distinct foliation and are typical gneisses.

In the present paper the term *gneiss* is employed to designate a rock which has a gneissic structure, but when used it is qualified by indicating the mineral composition of the rock—e.g., biotite gneiss, pyroxene gneiss, etc. Certain classes of rocks although they may display a gneissic structure are designated by special names e.g., charnockite, granulite, etc.

As Coomaraswamy observes, if gneiss be defined a silicate rock possessing a gneissic structure, practically all the Archean rocks in Ceylon, apart from the limestones and quartzites, are gneisses.

The term "granulite" has been used in several entirely different senses. It was first given to certain rocks in the so-called "Granulitgebirge" of Saxony. This classic area presents a variety of petrographical types concerning whose origin and mutual relations much has been written and many diverse opinions have been expressed. The occurrence is apparently a batholith of pale pink fine-grained acid quartz—orthoclase gneiss known as normal granulite or "Weissstein", associated with which, especially around the border of the area, are many dark or even black highly pyroxenic basic rocks, having the composition of diorite, norite and even pyroxenite. These are intimately associated with and often finely interbanded with pink normal granulite, the two rocks presenting a striking contrast in appearance. These dark rocks taken as a whole have been termed "pyroxene granulites" or "trap granulite". Both the normal granulite and the pyroxene granulite frequently contain grains of pink or red garnet. The pyroxene granulites furthermore often display a uniformity in grain and a more or less massive character.

Lehman (47) who has made the most recent and exhaustive study of the Saxon granulite district considers that the pyroxene granulite represents inclusions of the wall rock partly absorbed by a body of acid instrusive magma represented by the normal granulite, the whole having been subjected to subsequent dynamic action.

The term "granulite" may thus include the whole range of plutonic igneous rocks from granite to pyroxenite. Most of the silicate crystalline rocks of the Island might thus be designated as granulite were the term employed with this wide signification, but the Ceylon rocks differ in structure and in mode of occurrence from the Saxon rocks.

Among the French petrographers the term granulite is used to designate a granite containing both white and black micas and having a granular structure. In English it is often used for an aplitic rock, while in Sweden it is employed for the whole upper part of the "gneiss formation". The term has been applied by other writers to a highly garnetiferous gneiss.

Again, the crystalline rocks of Ceylon have been stated to represent a southern extension of the "Charnockite Series" of southern India. That the Charnockite Series does occur in Ceylon is undoubted, but as explained below it is necessary to define accurately the sense to which the term charnockite is to be used before applying it to the rocks of this Island.

The crystalline rocks of Ceylon will be divided into the following six classes:

1. The quartzose biotite gneisses.
2. Charnockite and rocks allied to charnockite.
3. The granulites.
4. Highly altered rocks of sedimentary origin.
   a. Limestones.
   b. Sillimanite garnet rocks (khondalite).
   c. Quartzites.
5. The Galle series.
6. The Balangoda series.

The character of the rocks constituting these several subdivisions of the Archean will first be described and the relations of the series to one another will then be discussed. A detailed petrographical description of typical rocks of each class will follow on under another heading.

The Quartzose Biotite Gneisses

These rocks are composed of quartz and orthoclase with some plagioclase and a little biotite. They are more or less distinctly foliated and belong to the very common and ordinary varieties of such gneiss which are met with in many Archean areas in various parts of the world, and which underlie thousands of square miles in the Canadian Shield. They form the basement rock over the greater part of Ceylon. As well known and easily accessible localities on the Island where these gneisses are well seen, Anuradhapura and Sigiriya may be mentioned. The great monastic buildings and monumental structures of the former, an ancient capital of Ceylon and one of the most renowned of the "buried cities" of the East, were built of a fine-grained orthoclase gneiss, reddish, pinkish or pale yellowish in color, and quarried in the vicinity.

The fort of Sigiriya, situated 35 miles to the southeast of Anuradhapura, stood on the summit of an almost circular erosion remnant of this gneiss which rises to a height of about 600 ft. above the level of the surrounding plain with sides so precipitous that its summit would be quite inaccessible without the aid of the ladders, overhanging around the whole periphery. This great column of rock affords a striking vertical section cut through a thickness of

some 600 ft. of this gneiss in a direction at right angles to its foliation and banding, which in part of the rock is horizontal and in others inclined at low angles. The gneiss here consists of several varieties intimately associated with one another. Some of it is the very common type of coarse-grained pink orthoclase gneiss with streams and flares of coarse pegmatite. Associated with this are large bodies of dark micaceous and in some places hornblendic varieties of gneiss. All have grains of red garnet more or less abundantly scattered through them. The great rock displays a magnificent section of gneisses with twisted, curving and contorted foliation, coarse and fine, darker and lighter, with schlieren of pegmatite and some great inclusions of dark highly hornblendic rock resembling amphibolite, the whole identical with hundreds of occurrences in the Laurentian of Canada, and suggesting in appearance an advanced stage in the digestion of masses of some basic rock by an invading magma now represented by the acid gneiss. These gneisses are also well seen in the exposures which from time to time outcrop on the summits of the low undulations of the coastal plain which are crossed on the road between Wellawaya and Pottuvil, a village on the southeastern coast of the Island.

The Charnockites and Allied Rocks

In the year 1900 Holland (40) described from southern India a series of igneous rocks to which he gave the name of the Charnockite Series. These formed a petrographic province, the members of which range from a highly acid hypersthene granite (charnockite) through hypersthene quartz diorites (and possibly monzonites), norites and other intermediate rocks to a basic hornblende hypersthenite. The characteristic iron magnesia mineral in all members of the series is a hypersthene rich in iron.

As it was difficult if not impossible, to delimit the occurrences of these various varieties of rock, Holland in order to facilitate the mapping of southern India, designated the whole group as the Charnockite Series and mapped it as a unit. He, however, urged the importance of confining the term Charnockite Series to the rocks of India.

While this whole group was called the Charnockite Series, the rock from which this name was derived and to which Holland gave the name charnockite was the most acid member of the series, a hypersthene granite, of which the type occurrence was found in the central part of a low hill immediately adjacent to St. Thomas' Mount, eight miles south of the city of Madras. Norite occurs on either side of this charnockite and forms the rest of the hill in question.

Subsequent to the discovery of members of the Charnockite Series at this locality, the rocks of the same series were found to make up the mountain masses of Shevaroys, the Nilgiris, and the Palnis and the great ridge of high ground forming part of the Western Ghats, and stretching as far southward as Cape Comorin (40). The plateau of the Nilgiris which alone covers an area of over 700 square miles is composed almost wholly of this series. Bergt (9) states that one of the Indian areas underlain by this Charnockite Series has an extent of 10,000 square miles.

In Ceylon a series of rocks which evidently represent a southward continuation of this Charnockite Series of southern India occupies large areas in the south central portion of the Island.

The characteristic features of this Charnockite Series as contrasted with the other classes of Archean rocks on the Island, is their prevailing dark grey to black color and the invariable presence of pyroxene in them, usually a highly ferriferous rhombic pyroxene (hypersthene), with which is associated in some cases a monoclinic pyroxene closely resembling it in appearance. There is as a general rule no other dark iron magnesium mineral in the rock.

These features mark it off rather sharply from the gneisses already described and from the other crystalline rocks of the Island which are reddish or pale grey in color and whose dark constituents, if any be present, are biotite or hornblende.

It is probable that in Ceylon the whole succession of rocks constituting the petrographical province of the Charnockite Series of southern India could be found if a careful search for them was made.

An important fact which is emphasized by Holland in his description of the Charnockite Series in India is that rocks composing it, while they are believed to be of plutonic igneous origin and to be intrusive in the older gneisses, very frequently show a departure from a strictly massive form and display a "schlieren" or streaky character, which in places passes into a banded structure. He mentions "that the slight differences of composition between adjoining streaks give rise to different powers of resistance to the action of atmospheric agents with the result that the so-called banding is always especially noticeable on weathered surfaces" and goes on to say "I believe the banding to be due merely to distortion of the imperfectly formed schlieren by flow of magma during the process of consolidation" (40).

This same schlieren structure is seen in the rocks of the Charnockite Series in Ceylon, accompanied by a more or less well marked tendency to a lining out of the constituent minerals in the direction of the schlieren or streaks. The movements which developed this structure undoubtedly took place, as Holland found to be the case in the Indian rocks, while the magma was moving during its period of consolidation.

It seems probable that the Charnockite Series in Ceylon is represented on the whole by more acid members of this petrographical province than in India. The varieties selected for analysis, as typical of the Series as developed in Ceylon, proved in most cases to be true charnockites in the narrower sense of the term, that is, hypersthene granites or closely allied rocks although generally containing about 10% less silica than the charnockite from the type locality near St. Thomas' Mount. On the geological map accompanying this paper the rocks of this series in Ceylon are designated as "Charnockites and Allied Rocks".

In Ceylon as in India, however, the series presents a variety of rock types and these could be subdivided and separately mapped—if indeed this is at all

possible—only by long continued and very detailed field work. In the map accompanying this paper, however, it is believed that the areas occupied by the "Charnockites and Allied Rocks" are shown with approximate accuracy.

These areas are as follows:—

a. The High Central Area, roughly triangular in shape, occupying the highest land on the Island, at the angles of which are Ramboda, Haputale and Adam's Peak.

b. The Bulutota mass which lies immediately to the south of that just mentioned.

c. Three small occurrences on the southern coast line at Galle, Weligama and Dondra Head, respectively.

d. An area stretching to the northeast from Colombo.

The High Central Area

The boundary of the eastern side of the area starting from Ramboda follows a southeasterly course to a point six miles southeast of Nuwara Eliya and from thence passes just east of Haputale to the outskirts of Koslanda. Then turning to the west it runs along the escarpment of the third peneplain to the vicinity of Adam's Peak. While the writer had not an opportunity of visiting this renowned mountain, Diersche (39) states that Zirkel on his visit to Ceylon found the rock at the foot of Adam's Peak to be a "pyroxene granulite", the feldspathic constituent of the rock being chiefly plagioclase, a little orthoclase and quartz being also present, the darker constituents being hypersthene, a monoclinic pyroxene with a little hornblende. It is thus probably a noritic rock such as is elsewhere associated with the charnockite. On the western side of the area the boundary, as shown on the map is sinuous, three lobes of the charnockite extending out into the adjacent quartzite formation. The precise petrographical character and chemical composition of typical representatives of the charnockite and allied rocks of this area will be found in the section dealing with the petrography of the charnockites.

As will be mentioned again later, the area mapped as "Quartzites, etc." and which lies to the west of this occurrence of charnockite rocks, comprises beds of quartzite, thin beds of crystalline limestone and bands and beds of dark gneisses which often hold hypersthene or monoclinic pyroxene, and which in character approaches certain rocks of the Charnockite Series. The origin of these rocks and their relations to the charnockite must be determined by further investigation.

Beyond but near the western and southern borders of this charnockite mass, furthermore, certain of the gneisses hold pyroxene, either rhombic or monoclinic or both, and thus in composition have a certain resemblance to the rocks of the Charnockite Series. Their relation to the biotite gneisses is a very intimate one, and again can only be determined by a very detailed study of the district.

Pidurutalagala, just north of Nuwara Eliya and the highest point in Ceylon, judging from the exposures around it is also composed of charnockite or one of the allied rocks of the Charnockite Series. Melzi (48) states that he found this mountain both on its slopes and summit to be composed of "pyroxene granulite", which is a name by which he would probably designate the rocks of the Charnockite Series. Zirkel[1] however found quartzite in place on the top of this mountain. It is probable that both observations are correct and that while the mountain is composed of rocks of the Charnockite Series, some quartzites belonging to the Quartzite Series above mentioned as bounding this Central Area of charnockite on the west, are associated with the charnockites on this summit peak of Ceylon.

One of the finest developments of charnockite on the Island is that at Haputale. This is a station on the Ceylon Railway and is situated on a long narrow extension of this central charnockite area to the east, as will be seen in the map. It stands on the southern margin of a depression in the highest peneplain. The road going from Haputale to the south winds down the face of a precipice by which the country falls off to the level of the lowest or coastal plain. This precipice cuts through an enormous instrusion of charnockite which is magnificently exposed on this road. This mass has the form of a great sheet intruded into the gneisses parallel to their bedding, striking N.80W. and dipping with the gneisses in a northerly direction at an angle of 30°. The rock is fine in grain, dark greenish-grey in color, displays an almost greasy lustre and closely resembles the charnockite from the original locality at St. Thomas' Mount. It is almost uniform in character throughout, shows a tendency to parallel arrangement of the constituents and occasionally on the great verticalfaces of the exposures somewhat darker narrow streaks or schlieren can be seen following long sinuous lines and in places doubling back upon themselves representing the flow movements of the original magma. The intrusion measured at right angles to its dip has a true thickness of no less than 2,000 ft. At mile post 111 on the road running south from Haputale a thick bed of vitreous quartzite is seen enclosed in the middle of this charnockite conforming in dip and strike to the latter.

A detailed petrographical study has been made of the charnockite of this intrusion at two points—namely, the upper surface and at a point 320 ft. below the surface. The results of these studies will be found under the heading "Petrography of the Charnockites". This great intrusion is overlain by the sillimanite gneiss and associated rocks which are exposed on the road just north of Haputale. It is underlain by quartzite, garnet sillimanite gneiss, etc. excellently exposed on the outskirts of the village of Koslanda, and at the fine waterfall of Diyaluma near this village where a stream drops vertically for 570 ft. over the basset edges of a series of alternating beds of garnet sillimanite rock, white quartzite (with or without garnet) and gneiss, presenting the appearance of a highly metamorphosed series of sedimentary rocks.

[1] *Quoted by Diersche from an address delivered by Zirkel in 1894.*

Eight miles east of Haputale the highlands of the third peneplain fall off abruptly toward the level of the second peneplain and the charnockite mass being confined to the high levels, ends at the face of the cliff. To the west of Haputale this charnockite passes into that lying to the east of the great development of quartzites, etc., to which reference is made above, and apparently forms part of one and the same intrusion.

The following localities, from which charnockites are described in the chapter on the Petrography of the Charnockites, are situated in the High Central Area—

Haputale (two occurrences),

Hatton,

Nuwara Eliya (two occurrences).

The Bulutota Mass

The Bulutota Pass crosses a high ridge which runs east and west on the strike of the country rock and lies just south of Rakwana and about 10 miles south of the High Central Mass of charnockite just described. This pass cuts through a great intrusion of charnockite which resembles very closely in petrographical character and mode of occurrence the Haputale occurrence just described. Like it also it has the form of a great sheet nearly horizontal in position. The exact line at which the base of this intrusion crosses the road which ascends the pass is not seen, the contact being mantled by red lateritic clay but it is above Rakwana and apparently very close to the 2,000 ft. contour. From this level the charnockite is continuously exposed on the road up to the summit of the pass, which is 2,800 ft. above sea level. The intrusion is therefore exposed on the pass for a thickness of 800 ft. Above the pass, the great east and west ridge through which it cuts rises to elevations of 4,300 ft. If this ridge therefore is composed of charnockite up to its summit, as seems probable, the Bulutota intrusion will be exposed for a thickness of 2,300 ft., which is almost exactly the "apparent" thickness of the Haputale mass.

Like the Haputale intrusion this Bulutota mass has a tendency to parallel arrangement of constituents with occasional curving streaks of darker color which show the direction of the flow in the original magma. The exact width of this intrusion in a north and south direction is not as yet known. It does not extend south as far as Morawaka nor to the west is the charnockite seen on the road running from Ratnapura to Panadure on the coast. To the east the high ridge formed by the intrusion becomes rapidly lower and nine miles from the Pass, sinks to the level of the Coastal Plain.

It is probable that the boundary of the intrusion as shown on the map is essentially correct, the mass being about 16.5 miles long and three miles wide. It is an erosion remnant, having been carved out of a sheet which formerly had a greater extension than at present, the high land which it occupies being now isolated by the processes of denudation.

From the summit of the Bulutota Pass, looking north, there is seen on the other side of a wide and deep valley the great escarpment whose summit is formed by the Haputale intrusion, and the possibility suggests itself that both masses may be parts of one great sheet separated by the erosion of the valley between them. It seems better, however, in the present state of our knowledge, to consider them as two separate intrusions, although closely resembling one another.

The Small Occurrences of Charnockite on the Southern Coast Line

There are three of these occurrences. The first is that which occurs on the outskirts of the city of Galle and which is extensively quarried by the Public Works Department for road metal. The charnockite as exposed in this quarry closely resembles that described by Holland from St. Thomas' Mount. It is very dark grey, nearly black in color, and nearly uniform in character throughout. It has a streaky structure and has a more or less well marked foliation, which is especially distinct on the weathered surface. The streaked structure is due to a certain variation in the proportion of the ferric constituents present from place to place across the strike. The foliation is vertical and there are a few coarser bands which approach a charnockite pegmatite in character. The rock weathers into a soft mass in which the structure of the charnockite can still be traced and this, near the surface, passes into a yellow clay in which all structure disappears. A petrographical description of the rock together with two chemical analyses of it is given below in the section dealing with the petrography of the charnockites (Table I, G & H.)

The mass seems to be lenticular in shape, the longer axis coinciding with the strike of the country rock, but as the surrounding area is covered with superficial deposits the outline of the mass cannot be readily traced.

About two miles from this large quarry there is another smaller one in which charnockite is again exposed. This presents two varieties of the rock, one of which is lighter in color and called by the quarrymen "glass rock". This is a highly acid variety, an analysis of which is given in Table I.–I. The second variety, which is apparently a differentiation product of the first, is darker in color and richer in ferric constituents.

The second occurrence is at Weligama Bay. This was not visited by the writer but is stated by Parsons (53) to be composed of a "micaceous norite".

The third is that forming the promontory of Dondra Head where the well-known lighthouse is situated, marking the extreme southerly point of the Island (see Plate IXb.). The charnockite here is medium in grain, dark in color, and shows the same streaked structure as at Galle, and has also a distinct foliation. A further reference is made to it in the section dealing with the petrography of these rocks.

The Area Stretching Northeast from Colombo

The road running in a northeasterly direction from Colombo to Kegalla passes first over the coastal plain, the only exposures being of "Kabook" or laterite, which is seen at intervals. Between Mahara, where the first fresh

rock is seen to a point beyond Udukumbura, a distance of about 35 miles in a northeasterly direction, charnockite crosses the road and is well seen in a series of small quarries which have been opened up by the roadside for the purposes of obtaining road metal. This rock is nearly black, of medium grain, and in many places practically massive, but in others an indistinct foliation or tendency to parallel arrangement of the constituent minerals is seen with a strike which varies from N. 10° W. to north and south, and which shows a dip of from westerly at an angle of 45° to a vertical altitude.

The quarries at the following points afford excellent exposures of this rock. Half a mile west of the Rest House at Mahara on a small side road, Kongahadeniya, the Hedidenikanda quarry, at mile post 36 a mile from Ambepussa, and near mile post 40. At all these places the rock is very similar in appearance and in petrographical character. A detailed description of that from the Hedidenikanda quarry is given in the section dealing with the petrography of the charnockites and an analysis of the rock will be found in Table I–J.

These rocks often display the streaked structure mentioned as being seen in so many of the other charnockite masses, suggesting movements in a mass not yet completely solidified. In places the rock is seen to be intruded by large bodies of pegmatite which cut across the indistinct foliation and the pegmatite itself in places shows a slight tendency to foliation in a direction which is identical with that displayed by the charnockite, as if the movement which produced the indistinct foliation of the charnockite, while antedating the intrusion of the pegmatite, did not entirely cease until after this intrusion had taken place.

Charnockite, very similar in character, is also exposed on the road between Colombo and Ratnapura, about 12 miles from the former place, also at Colombo itself and near Ruanella. The country between these points is largely covered by residual soil, and it is therefore impossible without a very detailed study of the whole area to determine the boundary of the mass to which it is thought that all these occurrences may belong. Whether they all belong to one and the same mass is conjectural, but they have been so represented on the accompanying geological map.

The Granulites (or Leptynites)

This name, as already mentioned, was first applied to a pale pink, often nearly white rock, which is the chief member of the well-known and much discussed group of rocks which occur in the "Granulite Region" of Saxony (47). French writers have frequently used the name Leptynite for this rock, a term which Coomaraswamy has adopted in referring to these rocks in Ceylon. On account of its very light color, the older writers in Germany often called it "Weissstein".

As used in the present paper this name is applied to a rock which is fine in grain so that a lens is often required to make out its character in the hand specimen. The extremely fine often microcrystalline varieties which are

common in Saxony are not found in Ceylon. The rock while not differing greatly in composition from certain varieties of the common orthoclase gneiss has a peculiar and striking appearance owing to its white or pale pink color, and to the fact that it often has an almost massive look (see Plate VIIIa). The presence of red garnets in individuals of considerable size scattered at intervals through the light-colored groundmass of the rock makes its appearance still more striking. The pale color of rock is due to the fact that femic minerals (with the exception of garnet) are practically absent. The rock consists of quartz and of feldspar which is usually microperthitic. When carefully examined the rock is seen to possess a foliation—some of the quartz being present in the form of minute leaves lying parallel to one another while the rest of the quartz is granular in character and associated with the feldspar in the groundmass. The rock is very poor in accessory constituents. Among these accessory constituents is sillimanite, which is found in small amount in some granulites. When this sillimanite becomes very abundant the rock has close affinities with the garnet-sillimanite rocks described under another heading.

There is a significant fact with reference to the mode of occurrence of these granulites—namely, that they are very frequently found in close association with beds of quartzite and crystalline limestone having themselves the form of beds apparently interstratified with these highly metamorphosed and very ancient sediments, in such a way as to suggest that they too are highly altered sediments.

The petrographical character and chemical composition of a number of typical granulites is described under another heading.

The Crystalline Limestones

The presence of numerous bands of white crystalline limestone in the Archean (or pre-Cambrian) of Ceylon is one of the features which give to this ancient series a striking resemblance to the Grenville Series of the pre-Cambrian of the Canadian Shield in eastern Canada and the Adirondack Mountains of the State of New York. The limestones are identical in appearance with those of the Grenville Series. They are white in color and range in size of grain from rather fine to very coarse. They as a general rule contain darker streaks, here and there running parallel to the strike, caused by the presence of grains of various silicates, these being identical with those found in the Grenville limestones. Among these, however, forsterite is especially abundant, while in Canada this mineral is rarely found in the limestones, its place being taken by pyroxene which is very common. On the weathered surface also they are identical in appearance with the Canadian limestones.

These limestones in Ceylon have been regarded by one or two observers as probably of igneous origin, because offsets from them have been observed running across the strike of the adjacent gneisses. This has been seen occasionally in the limestones of the Grenville Series in Canada but is merely due to the fact that limestone is a very plastic rock and that under the pressure to which it is subjected during folding it is forced, or will pass by plastic deformation,

into cracks or fissures in the adjacent silicate rocks which, being more brittle, are broken by the action of the same forces. Some such idea was entertained with reference to the origin of the Grenville limestones in the early days of geological investigation in Canada, but this has been long since disproved by further field studies, in fact, in Canada these great bodies of crystalline limestones, identical in character with those of Ceylon, have been traced step by step over into fine-grained bluish limestones of undoubted sedimentary origin and still retaining their organic coloring matter.

These Ceylon limestones are also undoubtedly altered sediments.

The limestones occur in the form of beds whose course conforms to that of the strike of the adjacent country rock—often a number of small beds occur together separated by intervening bands of gneissic silicate rocks. The maximum width which a single band has been observed to attain is a quarter of a mile (29). Beds often have widths of two hundred to three hundred yards.

All the occurrences of limestone observed by the writer or mentioned by any former observer are shown on the accompanying geological map.

The most important limestone developments consist of two well-defined bands which have been designated as the Badulla and the Matale Bands, respectively. A third important development consists of a number of shorter bands which occur in the southern part of the Island, in the Rakwana district. As the course of these limestone bands is a very important factor in working out the structure of the Archean area of the Island, this has been described and discussed in detail under the heading "Geological Structure of the Island" and need not be further referred to here.

In chemical composition they range from pure carbonate of lime or calcite through magnesian limestones to dolomites, and, in a few cases, to carbonate of magnesia or magnesite. Probably they are on an average more highly magnesian than the Canadian occurrences. Their petrography and chemical composition are described later in this paper.

The Sillimanite Garnet Rocks (*Khondalite*).

Coomaraswamy (18, 20) has mentioned the occurrence of certain sillimanite garnet rocks in Ceylon. These are of very special interest on account of the resemblance which they bear to certain of the "khondalites" of southern India —a series of rocks which in that country overlie the charnockite series and are believed to be, in large part at least, of sedimentary origin. He says that these rocks have rarely been found in situ and that it has not been possible to study closely their relation to the charnockites, but that they do not overlie them as in India and that transitions between these Sillimanite Garnet Rocks and the typical Leptynites can be frequently observed. He mentions them as occurring at many places between Bandarawela and Gilimale, as well as near Pattipola and on the Horton Path. He goes on to say that sillimanite-bearing rocks are found more sparingly in other districts, as at Kandy and at Kolonna and Matara in southern Ceylon.

These sillimanite garnet rocks were found by the writer in several places not mentioned by Coomaraswamy, the largest development being in the district about Passara and Namunukula, which places lie about 11 and 14 miles respectively northeast of Bandarawela. All these occurrences then lie in the western side of the province of Uva and are, as already mentioned, associated with quartzites and crystalline limestones.

The magnificent section at the Falls of Diyaluma near Koslanda, already mentioned in connection with the Haputale charnockites, where 628 ft. of nearly horizontal strata are exposed on their basset edges, affords additional exposures of garnet sillimanite rocks interbedded with white quartzite, which in some beds hold garnet, and with gneissic rocks. This has not been examined in detail.

The sillimanite garnet rocks from four typical occurrences have been studied petrographically and chemically. The results of these studies are given below in the section dealing with petrography. (See Analysis A, B. C. D, Table V and Plate VIII, b and c).

The question of the origin of these rocks is one of much interest. Their usual association with limestone and quartzite and sometimes their appearance in the field suggests that they are of sedimentary origin. Their chemical composition strongly supports this supposition.

In 1917, H. S. Washington (66) assembled the chemical analyses of igneous rocks which had been published between the years 1884 and 1913 and discussed them critically. In this publication the analyses of 8,602 igneous rocks are given. None of the igneous rocks in Dr. Washington's paper fall within either of the divisions of the Quantitative Classification which contain rocks A and B, respectively. No fresh igneous rock having the chemical composition of either of these rocks had been analyzed up to the time when this work was published.

Rocks C and D of Table V resemble one another very closely in composition and come into the same division of the Quantitative Classification. In this division there are but four rocks recorded, all of which again have a much lower content of alumina than C and D. On examining Dr. Washington's paper with some care only two analyses of igneous rocks were found whose composition was approximately similar to that of these rocks, and one was a "dyke rock" described by v. Groddeck from Chili and the other a cordierite andesite from Cabo de Gata described by Osaan. Both of these rocks are higher in magnesia and lower in alkalies than the two Ceylon rocks under consideration. It is evident that if there are any igneous rocks which possess the peculiarities of chemical composition seen in these rocks, they must be very few in number.

When on the other hand the analyses of sedimentary rocks are examined it is found that many shales closely resemble these sillimanite garnet (C and D) rocks in composition. F. W. Clarke (15) gives a composite analysis of 51 Palæozoic shales. This analysis shows H_2O, C, and CO_2 amounting together

to 7.05%. This analysis has been recalculated to show the composition of the rock if these substances were eliminated—as they would be under intense diagenetic metamorphism—and the result is given in Table V. E.

This composite analysis of these shales shows a striking resemblance in composition to that of the Ceylon sillimanite garnet gneisses C and D. The analysis of two phyllites from Saxony and of a sillimanite garnet gneiss from the Grenville Series (Pre-Cambrian) of the Canadian Shield occurring at St. Jean de Matha, north of the Island of Montreal (3), are also added for further comparison (Table V, F, G and H). The last rock occurs interstratified with beds of garnetiferous quartzite and is believed to be of sedimentary origin.

The value of the chemical composition of a metamorphic rock as a criterion for the purpose of deciding whether the rock from which it was derived is of igneous or sedimentary origin has been discussed by several writers (3, 7, 39a, 47a, 57a, 60a).

Leith and Mead whose contribution to this subject is one of the most recent after a somewhat extended study of the question, came to the conclusion that chemical criteria do not as a general rule afford a basis for the discrimination of metamorphic rocks of igneous origin from those of sedimentary origin, since in many cases metasomatic changes have been brought about in the rock by the addition or substraction of certain elements during the process of metamorphism, which alter the composition of the rock and thus mask its original chemical constitution.

Chemical evidence however may, they consider, be of value in certain cases where it is supported by other evidence. This is undoubtedly true, but Bastin after a careful study of the subject, has reached the conclusion that as metamorphic changes are often of a diagenetic character, taking place without any substantial alteration in the chemical composition of the rock, there are certain cases, probably relatively few in number, in which the chemical composition of the metamorphic rock affords very important if not conclusive evidence concerning the igneous or sedimentary origin of the rock in question. He has set forth categorically the several points in which a schist or gneiss formed by the metamorphism (diagenesis) of a shale differs from that derived from the corresponding alteration of an igneous rock. These are as follows:—

1. The presence of alumina in a ratio considerably in excess of 1:1 as compared with the combined amount of lime and alkalies present, this being the ratio in which it is present in the common rock making silicates.
2. Dominance of magnesia over lime.
3. Dominance of potash over soda.

It is to be noted further that Bastin arrives at the conclusion that a sedimentary origin may be suspected if a fresh metamorphic rock shows an excess of alumina over combined lime and alkalies of 5% and that when the excess exceeds 10% a sedimentary origin is extremely probable. Applying these criteria to the four Ceylon garnet sillimanite rocks under consider-

ation, rock A shows an excess of alumina amounting to 1,700%, rock B an excess of 490%, rock C of 100%, and rock D of 90%. In the second place, in all four rocks there is a marked excess of magnesia over lime.

In connection with the third point, it is to be noted that in rocks A and B about five times as much potash as soda is present, in D there is a marked excess, in C there is a slight excess of soda—38 molecules of soda to 31 of potash.

It seems then extremely probable that these four sillimanite garnet rocks occurring as they do more or less intimately associated with beds of quartzite, or limestone whose sedimentary origin is practically indisputable, and having the distinctive chemical composition which they display, are highly altered argillaceous sediments.

The first two of these rocks have such a high content of alumina that they fall into Sub-Class 2 of the Quantitative Classification in which the ratio of quartz + feldspar + lenads to corundum + zircon is less than 7/1. In the first of these the alumina and ferrous iron ore are so high that the possibility is suggested that this rock was originally the product not only of the ordinary processes of decay that are now at work in extra-tropical lands, but that in its production the peculiar and still somewhat obscure process which gives rise to the laterites of the tropics played a part, and that the climatic conditions in Ceylon at that time resembled, in certain respects at least, those of the Island at the present day.

The Quartzites

These rocks are exposed at a number of places in the southern half of the Island and are usually intimately associated and often interbedded with the limestones. Their most extended development is in the large area on the high lands of south central Ceylon shown on the map as "Quartzites, etc.". Here the rocks which lie in low undulations and are often flat, consist of quartzites interstratified with thin beds of limestone and with a dark gneiss. This gneiss as exposed at mile post 2 on the road between Nawalapitya and Dimbula is found under the microscope to be composed essentially of orthoclase and quartz, with diallage and hornblende in about equal amounts and a little garnet. Iron ore, pyrite, apatite and zircon occur as accessory constituents. In specimens of the gneiss from other points on this road pyroxene is absent and its place is taken by hornblende and biotite. Plagioclase is usually absent in these gneisses.

At intervals all along this road crossing the area between these two villages, heavy beds of quartzite outcrop, as is also the case on the road running off at right angles to it between Dimbula and Hatton. Quartzite is again exposed about 3.5 miles west of Ginigathena (mile post 59.5) in the same area. Here it is of a buff color, well and thinly bedded and shows a very distinct foliation. It is medium in grain and is composed of quartz with much less orthoclase. In some beds there are a few flakes of biotite, in others this mineral is absent and the rock is composed essentially of quartz with accessory orthoclase. These minerals are arranged in the form of minute laths, flattened in two

directions with an irregular cross section in the third which is at right angles to the dip. The orthoclase is somewhat turbid from incipient decomposition, the little laths or "stenglige" of this mineral lying between, or sometimes within, those of the quartz. The quartz shows a faint undulatory extinction. The rock has evidently undergone recrystallization under pressure and movement.

Heavy beds of quartzite associated with crystalline limestone are also seen on the road about four miles north of Ratnapura, also in very large exposures and again with crystalline limestones and with sillimanite garnet rock in many places east and west of Passara, the series being much folded. Three and a half miles from Passara on the road to Badulla (mile post 8.5) the quartzite is composed entirely of quartz, rather coarse in grain, is traversed by many joint planes and breaks with an uneven hackly fracture. When thin sections are examined under high power, the quartz is seen to contain many minute fluid inclusions, sometimes with moving bubbles.

The quartzite occurrence at Koslanda and a great bed included in the Haputale charnockite intrusion have already been mentioned.

The Point-de-Galle Group

In 1902 Coomaraswamy described certain rocks which are found in and about the old town of Galle, on the southern coast of Ceylon, as the Point-de-Galle Group (26). He states that the chief rock types in the group vary from basic pyroxene sphene scapolite rock, through intermediate rocks composed of pyroxene, scapolite and wollastonite with feldspar and quartz subbordinate or abundant, to acid types made up of orthoclase-microperthite or a coarse-grained quartzo-feldspathic rock. They differ, he says, from the normal types belonging to the Charnockite Series in their somewhat coarser grain, in the presence of wollastonite, scapolite and sphene, in the existence of definite dykes and segregation veins crossing the foliation and in the absence of garnet, hypersthene, original mica and hornblende. The rocks, he states, may be classed as orthogneisses with the wollastonite and scapolite as original minerals. Or possibly the richness in lime may be due to the absorption of a mass of limestone by some rock of the Charnockite Series, in which case the lime silicates must be regarded as endomorphic contact minerals. Or again the local richness in lime may be due to a local variation in the constitution of the magma. The members of the series, he states, show a progressive differentiation from basic to acid types, the coarse segregation veins being the last product of the process, adding that the rocks have not suffered from earth movements since their complete consolidation, as shown by their microscopic characters, while the interlocking of the minerals at the junction of the segregation veins with the matrix shows that the veins are of contemporaneous character. The relation of this Galle Series and the charnockite to the biotite gneiss and limestones is uncertain and will remain so until this part of Ceylon is mapped geologically in detail and a very careful study of the district has been made.

The rocks along this southern coast of Ceylon are for long stretches covered by a red lateritic residual product, "Kabook", which about Beruwala, south of Kalutara, is extensively quarried for building purposes. Elsewhere they are mantled by alluvium. There are, however, many large exposures of the underlying crystalline rocks to be seen, expecially on the rocky points which from place to place jut out from the shore. The rocks of all these exposures along the coast show a distinct foliation which conforms to the great sweep which the strike makes around the southern part of the Island following (or rather being followed by) the course of the coast line.

Starting from Kalutara, a village on the coast situated 27 miles south of Colombo, and following the coast road to Dondra Head, the extreme southern point of Ceylon—one of the most beautiful stretches of country to be found anywhere in the East—the underlying crystalline rocks are exposed at a number of places.

At Maggona, 2.5 miles south of Kalutara, a grey banded gneiss is seen cut by pegmatite dykes holding black mica. The same gneiss with occasional darker bands and traversed by pegmatite dykes appears again six miles south of Kalutara. Under the microscope this gneiss is found to be composed of pyroxene, biotite, orthoclase, plagioclase, and quartz with iron ore, apatite and zircon as accessory constituents. Having pyroxene as one of its constituents it has an affinity at least with the rocks of the Charnockite Series.

Twelve miles south of Kalutara gneiss is again exposed. It is much contorted and consists of bands of schlieren varying considerably in color, the darker bands often pulled apart by the movement of the more plastic, or more fluid, lighter-colored bands. Some of the bands when examined under the microscope are seen to be composed of a deep green monoclinic pyroxene with orthoclase and quartz, and with zircon as an accessory constituent. The orthoclase frequently shows a minute microperthitic intergrowth, and some occasional grains show a micropegmatitic intergrowth of quartz and orthoclase. Other bands, nearly white in color, contain no femic constituent except large lumps of garnet, the other constituents being orthoclase (as before) and quartz with accessory sphene. These gneisses are cut by dykes of pegmatite, often as much as twelve feet wide, some of which hold a number of large inclusions of a dark color, which when examined are found to consist of an aggregate of white scapolite, deep purple fluorite, deep green diopside, brown zircon, with a little reddish brown opal. This association of minerals suggests that these inclusions were originally fragments of limestone which have been completely altered by the action of the pegmatite magma which enclosed them.

Large exposures of a grey gneiss rather uniform in general character are then seen at intervals along the coast to Galle. These show darker streaks at intervals, and are cut by pegmatite dykes. An examination of specimens of this gneiss collected at mile post 51, twenty-one miles from Kalutara, showed it to be composed of orthoclase, plagioclase, quartz, and pyroxene, with biotite, iron ore, zircon and pyrite as accessory constituents. Other specimens

collected at mile post 54, twenty-four miles from Kalutara, are composed of microperthite, plagioclase, quartz and biotite with zircon as accessory constituents.

It is worthy of note that zircon is very common as an accessory constituent in the rocks all along this southwestern coast of Ceylon, occurring sometimes in small rounded individuals but usually with a more or less distinct prismatic form, sometimes showing pyramidal faces as well. It is colorless in the thin sections and shows the high index of refraction and high birefringence characteristic of this species. At Matara, near Dondra Head at the extreme southern point of the Island, this zircon is found in colorless individuals sufficiently large to be cut and employed in jewelry, being known in trade as Matara Diamonds.

Galle was the chief port of southern Ceylon at the time of the Dutch occupation. The picturesque old fort situated on the shore at this place was built by the Dutch, but has now for the most part disappeared. It is in and about this Fort at Galle that the typical development of the Point-de-Galle Group of Coomaraswamy is found. The ramparts of the Fort have their foundations on large exposures of typical coarse-grained pegmatitic granite composed of quartz, alkali feldspar and biotite. This is associated with a very impure crystalline limestone which occurs in thin bands, a few inches in width, filled with various silicates and interstratified with bands of several varieties of fine-grained grey pyroxene scapolite wollastonite gneisses. The pegmatite or pegmatitic granite preponderates very largely and the whole resembles very closely hundreds of occurrences to be seen in various localities in the Grenville Series in the pre-Cambrian of Canada. It is of interest to note that the age of these pegmatites as determined by Holmes (41) from a measurement of the radioactivity of one of the constituent minerals is eight hundred million years.

Specimens of three of the commonest and most characteristic varieties of these gneisses were examined microscopically and were found to resemble one another closely in composition. They were all taken from the enclosure of the old Fort. They all show a distinct gneissic structure.

The first was found to be composed of pyroxene, scapolite and wollastonite with graphite, sphene and calcite as accessory constituents. The pyroxene is monoclinic, pale greyish-green in color and not pleochroic, probably belonging to the variety malacolite or diopside. It shows the usual characters of this mineral and is present in large amount. The scapolite displays the high double refraction, uniaxial and negative characters and cleavage with parallel extinction of this species. The wollastonite occurs in prismatic form, it is colorless and shows the biaxial character, inclined extinction and other optical characters presented by this lime pyroxene. The graphite is seen in the thin section as occasional slender black leaves and the sphene as rounded grains, light brown in color.

The second variety examined was found to be identical in composition with that just described except that no calcite but a little pyrite was present.

The third was identical in composition with the first except that it contained a little pyrite and a small amount of orthoclase. All three varieties show the same allotrimorphic granular structure, the wollastonite alone having a tendency to assume a more definite prismatic outline and the chief difference between the varieties is that in the first the pyroxene is relatively much more abundant than in the other two.

Specimens of rocks very similar to these gneisses collected in the vicinity of Salem in southern India have been examined and described by Lacroix (44) p. 249.

Following the shore road east of Galle, the rocks are largely covered by lateritic deposits, but James Parsons (53) states that the cliff on the west side of Weligama Bay is composed of a hard micaceous norite; that an island in the bay is of the same rock and another in the centre of the same bay is made up entirely of pegmatite. He notes the fact that in one place a "segregation vein" of scapolite contains apatite, which he says indicates that the pegmatite may be classed with the Galle Group of rocks. On the eastern outskirts of Matara a gneissic rock resembling charnockite in appearance is seen, while Dondra Head, the most southerly point of Asia, is composed of gneissic charnockite, and four miles east of Dondra Head charnockite is again exposed near the shore —beyond this to the east no charnockite or charnockite-like rock is seen.

Four miles to the east of this last occurrence of charnockite, at mile post 111, large exposures of white, highly quartzose gneiss with some darker bands much contorted, but with an east and west strike are seen. It is composed essentially of quartz with microline and microperthite and contains no femic mineral. On the surface it weathers out with little holes, giving to it a vesicular appearance.

The Point-de-Galle Group, as defined by Coomaraswamy (26), consisting of the pyroxene scapolite wollastonite gneisses and their associated limestones in thin bands, occupies a very limited area, which is within and immediately adjacent to the old Fort at Galle. It undoubtedly has a further extension beneath the waters of the ocean as it is exposed immediately along the sea coast. In the opinion of the present writer, the second of the several possible explanations of its origin, put forward by Coomaraswamy and mentioned above, is the correct one—namely, that it represents a small area of limestone which has undergone intense metamorphism through the intrusion of the great masses of pegmatite which penetrate it, and also possibly from the rocks of the Charnockite Series with which it is associated.

On the map accompanying this paper, it, together with the much larger volume of gneiss which lies to the east and west of it along the coast and possesses a distinctive character and may form part of it, or which may prove to be more nearly related to the Charnockite Series, has been represented by a separate color.

The Balangoda Group

These rocks, which are not represented in the geological map accompanying this paper, are a series of intrusive granites, most of which are characterized by the presence of zircon. The name was given by Coomaraswamy (30) and his paper dealing with them sets forth all that is known concerning them.

Coomaraswamy's general statement concerning the group is as follows:

"The name "Balangoda group" is proposed for a series of granitic and pegmatite-like rocks, intrusive in, but distinct from, the Charnockite Series; these rocks were first met with in the Balangoda district, but are evidently widely distributed over a large area between Balangoda and Hatton. The rocks are best described as granites, but occur most often in rather narrow dykes, after the manner of pegmatites. Yet there is no reason for separating the smaller from the larger masses, and the term granite is applied to both. The group (of which a more detailed account will ultimately be needed) includes in particular zircon granite, allanite granite, magnetite granite, and granite without conspicuous accessory minerals; as well as the probably similar rocks in which the hitherto unlocated minerals geikielite, baddeleyite, rutile, fergusonite, thorite, thorianite, etc., may be looked for; and the vein of pegmatite at Gampola, which consisted of quartz, feldspars, and biotite, with apatite, ilmenite, tourmaline, and the new mineral described as thorianite as accessory minerals."

The paper then goes on to describe certain of the more important developments of these rocks on the Island. It is probable that the pegmatites mentioned in the present paper as occurring in the "Galle Series" near Galle and elsewhere in the area shown in the map as underlain by the "Point-de-Galle Group" belong to these Balangoda intrusions.

Relations of the Several Classes of Rocks to One Another

This Archean area like every other complex of highly altered rocks which has been subjected to great orogenic movements requires to be examined in great detail before its history can be accurately deciphered. In the absence of such detailed study however certain relationships can be established with a high degree of probability. Thus the Badula, Matale and Rakwana limestone bands are found to belong to the same series as the biotite gneiss. Their bedding coincides with its foliation, and their course follows that of the strike of the gneisses with which they are so intimately associated. The same is true of the quartzites and of the sillimanite garnet rocks which also occur in close association with these limestone bands. These three classes of rocks are undoubtedly highly altered sediments as are also perhaps some of the beds of granulite which are found with them. Whether the biotite gneisses are of igneous origin and have been intruded into these sediments, or whether the biotite gneiss itself is wholly or in part of sedimentary origin is still uncertain. Probably however the greater part of it is of igneous origin and represents a great body of highly

acid magma which has invaded, metamorphosed and partly absorbed the sedimentary series. This view is supported by an examination of the fine section seen at Sigiriya, to which reference has already been made.

The numerous thin bands of limestone, and the quartzite interbedded with them and with dark pyroxene gneisses in the area mapped as "Quartzite, etc." seems to be a higher part of the same series. These pyroxene gneisses, however, resemble certain of the more highly foliated varieties of the charnockites. How it is related to these charnockites is not known. The Galle Series also, as mapped, seems to be closely related to, if not part of, the biotite gneiss series, containing however some charnockite material.

The determination of the relations of the charnockites to the other series in Archean of this area can only be decided by a much more detailed study of the field relations of these rocks than they have as yet received. In Ceylon the charnockites have not as yet been observed cutting across the rocks of the other series as they have been found to do in India, and other conclusive evidence showing that they are a later igneous series intruded into the complex just referred to, has not so far been secured. The clearest evidence that a part of the Charnockite Series at least is of igneous origin and is later than the complex in question is afforded by the Haputale mass which presents all the characters of a body of igneous rock which has been intruded into the great series of limestones, quartzites and gneiss parallel to the bedding and foliation of the latter. The charnockite northeast of Colombo also, if correctly mapped, cuts across the foliation of the biotite gneiss. On the other hand, whether the pyroxene-bearing gneissic rocks interstratified with the quartzites and limestones forming the occurrences on the higher part of the Island and designated on the map "Quartzites, etc." are of igneous origin and represent apophyses from the same great mass as that seen at Haputale could not be determined in the time at the disposal of the writer for field work in the area.

The same is true of certain occurrences of rocks related to the charnockites and which are intimately associated with granulites near Kandy. The rocks of the Charnockite Series at this locality have been referred to by several writers, as they occur in a locality which is visited by nearly every one who comes to Ceylon. The occurrence however occupies but a small area and has not been indicated on the accompanying map.

In all probability, however, the charnockites forming the "High Central Area" represent a great intrusive of plutonic igneous rock forced in an approximately horizontal direction into the upper part of the older series of limestones, quartzites, gneisses, etc., which now stands high above sea level and forms the highest portion of the Island.

Relation of the Archean of Ceylon to that of India

The Archean of Ceylon is undoubtedly an extension of that great development of rocks of this age which underlies the larger part of southern India.

The biotite gneiss in Ceylon evidently represents a southward extension of the "Bengal Gneiss" of India which holds intercalated bands of crystalline limestone and dolomite, khondalite, etc., closely resembling those described in the present paper.

The widespread occurrence of hypershene-bearing rocks of the Charnockite Series in Ceylon is another point of resemblance indicating a close relation between the Archean development of Ceylon and that of India from whence this Series takes its name.

As noted by Holland, after those of Ceylon the nearest foreign relatives of the Charnockite Series are the few exposures of "pyroxene-granulites" described from Madagascar and the mainland of Africa. The occurrence of these rocks in the great developments of rock of Archean age which are found in these countries is of special interest in view of the supposed existence of the pre-Tertiary Indo-African content—Gondwana Land—of which fragments are now believed to survive in Ceylon, South Africa, Madagascar, Peninsular India, Assam and elsewhere.

Dykes

It is a curious fact that apart from the pegmatites found with the biotite gneisses and in the Balangoda and Galle Series, dykes are extremely uncommon in Ceylon.

The largest and most interesting dyke on the Island is that described by Coomaraswamy (21) as a typical dolerite and which has a width of 95 yards and crosses the road just to the north of the Kallodai Rest House on the eastern side of the Island. It runs northwest and southeast for a distance of at least 30 miles, following a course in general parallel to the strike of the biotite gneisses which it cuts. It forms a well-marked topographic feature weathering into rounded stones and boulders which strew its course, bears a resemblance to the surface of a rough road and is called the Kallodai Causeway which is mapped in the ordinance survey of the Island.

(*To be concluded in the next issue of the Canadian Journal of Research*).